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Exploring the Dynamic Interplay between Globalization, Renewable Energy, Economic Growth, and Environmental Impact: Insights from the Saudi Arabian Development Perspective

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ABSTRACT

It is important to note that the relationship between energy use and economic growth within the framework of globalization for any economy can vary depending on national contexts, energy policies, technological advances, and environmental pressures. Sustainable and energy-efficient approaches are increasingly seen as essential to reconciling economic growth with environmental conservation. This paper studied the dynamic links between globalization, renewable energy consumption, industry evolution, economic growth, and pollution in the Saudi economy during 1990–2019. We found varied and mixed results by using causality tests based on the VECM model, supported by unit-root tests and co-integration. We developed this study by adding the impulse response function in order to detect the periodic effect of each variable. The main findings show that there are bi-directional links between energy consumption and pollution, as well as between renewable energy consumption and economic growth. The framework of sustainable development presented numerous policy recommendations aimed at achieving a green and sustainable economy for Saudi Arabia.

INTRODUCTION

Because of their interdependence and implications for the economy, environment, and society as a whole, people often discuss globalization and sustainable development together. The link between globalization, renewable energy, economic growth, and pollution is complex and deserves special attention. Globalization, by promoting trade on an international scale, has contributed to significant economic growth in many regions of the world. However, increased energy consumption and greenhouse gas emissions often accompany this economic growth, exacerbating pollution and climate change issues. Renewable energy plays a crucial role in the fight against pollution and climate change. By providing a clean, sustainable alternative to fossil fuels such as coal, oil, and natural gas, renewable energy helps reduce greenhouse gas emissions and mitigate the harmful effects of pollution on human health and the environment.

Additionally, renewable energy often provides economic benefits by enhancing total factor productivity creating local jobs and spurring technological innovation. Several studies support these arguments. Sohag et al. (2021) demonstrated that renewable energy drives long-term TFP growth through various macroeconomic channels, whereas fossil fuels show an inconclusive impact. In OECD countries, human capital and technological advancements play a pivotal role in boosting TFP. Similarly, Neffati et al. (2023) identified a strong positive long-term relationship between renewable energy and TFP growth in G20 countries but noted a negative relationship in G7 nations due to environmental repercussions. Granger causality tests reveal differing causal directions, highlighting the critical need for global investment in renewable energy to enhance productivity and ensure sustainable development.

In recent decades, there has been a growing focus among researchers and policymakers on the relationship between energy consumption, economic growth, and environmental pollution. Global society has also expressed growing concern about the escalating threats of global warming and climate change, both of which are closely linked to patterns of energy consumption. The heightened awareness of climate change gained significant momentum with the Kyoto Protocol's adoption in 1997. This international agreement mandated industrialized nations to curtail their greenhouse gas emissions, prompting a shift away from reliance on fossil fuels, particularly coal and oil, toward the adoption of renewable energy sources (RES) characterized by their minimal carbon footprint. As a result, the emphasis on increasing the proportion of renewable energy in overall energy consumption becomes paramount, as it proves to be highly effective in mitigating greenhouse gas emissions, as noted by Elliott in 2009.

According to seminal work by Sadorsky (2009), energy availability plays a crucial role in driving economic activity. Traditionally, coal, natural gas, and petroleum have been the predominant and most effective energy sources, contributing significantly to economic development (Ellabban et al., 2014). The demand for these conventional energy sources has surged over the past fifty years due to global economic and social advancements (Aslan et al., 2014). Traditional sources generated approximately 65% of the world's energy in 2013 (IEA, 2015). Nevertheless, in the early 21st century, countries worldwide have grappled with diverse energy-related challenges, marking a global concern regarding reliance on conventional energy sources (Sadorsky, 2009a). This dependence on traditional energy sources has given rise to issues such as energy poverty, fluctuations in energy prices, and an increase in carbon emissions (Destek and Aslan, 2017; Koçak and Şarkgüneşi, 2017).

In addition, climate change on a global scale refers to alterations in long-term weather patterns (Vijaya Venkata Raman, Iniyan, and Goic 2012). This phenomenon may arise from substantial shifts in the frequency of natural climate events or from various climate events triggered by human activities. Climate and weather factors primarily influence these events. Consequently, climate change emerges as a worldwide concern impacting all nations (Chinowsky et al. 2011). In various countries, observational studies examining the relationship between energy consumption, CO2 emissions, and economic development have yielded conflicting results. According to Chinowsky et al., there is a positive correlation between advanced technological development and increased atmospheric pollution, particularly in regions experiencing sophisticated economic growth.

Many countries are exploring alternative energy sources in production, such as renewable energy, to address environmental concerns and reduce carbon footprints. In this regard, the government of the Kingdom of Saudi Arabia (KSA) has formulated an energy policy with the goal of diversifying energy sources and suppliers, as well as fostering private sector involvement. This policy places particular emphasis on the development of renewable and nuclear power generation. The government has devised and implemented several energy efficiency projects, aiming to increase efficiency in the industrial, transportation, and residential sectors. In response to the escalating demand for power, the kingdom has launched a renewable energy program strategically aimed at reducing reliance on fossil fuels to ensure the country's sustainable future. Recognizing that depending on fossil fuels for future economic growth is not a viable and lasting option, the Saudi Arabian government is actively pursuing alternatives. Indeed, Saudi Arabia boasts abundant energy resources such as petroleum, natural gas, and solar energy. The country's diverse geological features and environments present promising opportunities for harnessing other forms of energy, such as wind energy, nuclear energy, and geothermal energy (Rehman and Shash, 2005). The Kingdom of Saudi Arabia deems the development of solar, wind, and thermal energy plants essential to meet its electrification needs.

The Gulf countries have a large abundance of solar energy throughout the year, which puts them in a privileged position to develop solar energy projects. The United Arab Emirates and Saudi Arabia, for example, have launched huge projects to harness this energy. Some Gulf countries have excellent potential to generate energy through wind energy projects. For example, Kuwait and Oman have begun to explore wind energy potential in the region. Some countries in the Gulf have expressed their desire to develop nuclear energy to meet the growing demand for electricity. The United Arab Emirates, for example, has begun construction of a nuclear power plant. The region faces environmental challenges, including high temperatures and water consumption. These challenges may affect the efficiency of renewable energy generation. The shift to renewable energy sources requires a change in the economic structure that relies heavily on oil and gas exports. Building renewable energy projects requires significant investments, and financing can be particularly challenging in light of low oil prices. In fact, Gulf countries aim to diversify their energy sources and take advantage of their natural resources to meet the growing demand for energy while reducing their environmental impact.

However, to our knowledge, few national and international studies on the link between globalization, total renewable energies, and the growth nexus, including industry evolution, are available in the literature review. Furthermore, in the case of Saudi Arabia, there is no study that has explored this relationship by including industry evolution. This is why we are going to use different estimates, like the Vector Error Correction Model (VECM) and impulse response function (IRF), to look into the connections between short- and long-term CO_2 emissions, economic indicators (GDP per capita), and the use of renewable and nonrenewable energy from 1990 to 2019. In fact, the KSA ranks 6th and 13th, respectively, in producing solar and wind energy.

We organize the rest of the paper as follows: Section 2 provides a literature review that examines the relationship between energy consumption and economic growth. Section 3 presents an overview of the energy sector in Saudi Arabia. Section 4 develops the theoretical VECM model and discusses the data set, including empirical results; and finally, section 5 concludes and offers some policy discussion for the Saudi context.

1. LITERATURE REVIEW

The link between economic growth and energy has been extensively examined, yielding empirical results that are often diverse and conflicting. Variability exists in the identification and direction of the causal link, as well as in the short-term and long-term implications for energy policy. The nature of this causality, whether unidirectional or bidirectional, plays a crucial role in determining the implications for energy consumption and growth rates (Ozturk, 2010). The lack of consensus in studies, even within the same country or geographical area, can be attributed to methodological disparities and differences in the considered databases. For instance, Kraft & Kraft (1978) analyzed annual data from 1947 to 1974 using the Granger method and found that growth "Granger causes" energy in the United States. However, Yu & Hwang (1984), using Sim's technique, found no such link between 1947 and 1979. Hwang & Gum (1991), employing the error correction method in Taiwan from 1961 to 1990, revealed a bidirectional relationship between energy and growth. In contrast, Cheng & Lai (1997) found a unidirectional relationship from GDP to energy in Taiwan between 1954 and 1993. Lee (2005) and Lee & Chang (2007) presented opposing results for developing countries. Lee (2005) discovered that energy "Granger causes" growth from 1975 to 2001, while Lee & Chang (2007) suggested a growth-to-energy relationship from 1965 to 2002 using the VAR and GMM method.

In studies on Korea, Glasure (2002) observed a bidirectional relationship with annual data from 1961 to 1990, where energy and GDP influenced each other. On the other hand, Oh & Lee (2004) found a unidirectional causal relationship, where energy causes GDP between 1970 and 1999. Soytas & Sari (2006) explored G-7 countries and identified three forms of links during 1960-2004: GDP causing energy in Germany, energy causing GDP in France and the United States, and mutual influence in Italy, Canada, Japan, and England. In contrast, Narayan & Smith (2008) found a unidirectional relationship where energy causes GDP in the G-7 countries over the period 1972-2002. Aspergis & Payne (2009) demonstrated that the causal relationship between energy and the product may evolve over time. Their study on commonwealth countries revealed a unidirectional link in the short term, where energy causes the product, and a bidirectional relationship in the long term.

Additionally, Apergis and Payne (2010) propose that a notable increase in renewable energy presents a viable alternative energy source. Al-Mulali et al. (2013) suggest that augmenting the share of renewable energy can diminish reliance on traditional sources, thereby ensuring energy security. The International Energy Agency (IEA) reported that there is an approximately 3% annual growth rate in renewable energy consumption, marking it as the fastest-growing global energy source (IEA, 2015). Recent trends reveal that governmental initiatives, such as incentives, tax credits, and subsidies, play a pivotal role in propelling the development of renewable energy. Presently, nations prioritize technology advancements and energy production from renewable sources, shaping the predominant elements of energy policy formulation. Some researchers have examined how structural changes in the economy, such as the shift from an industrial to a service economy, can influence the relationship between energy consumption and growth.

Several notable studies have delved into the relationship between energy and economic growth, providing compelling insights. One such study outside of Africa is conducted by Apergis and Payne (2010), who investigate the impact of renewable energy consumption on economic growth in twenty OECD countries from 1985 to 2005. Apergis and Payne (2010) extend this analysis to 13 Eurasian countries, and in a separate study, they explore six Central American countries, utilizing the same production function. Expanding their scope, Apergis and Payne (2011) incorporate non-renewable electricity consumption into their production function, focusing on 16 emerging market economies. Although the estimated coefficient on renewable electricity consumption is positive, it is not deemed statistically significant. In a broader study spanning 80 countries from 1990 to 2007, Apergis and Payne (2012b) find that a 1% increase in renewable energy consumption correlates with a 0.371% rise in real GDP.

Al-mulali et al. (2014) compare the roles of renewable and non-renewable electricity consumption in driving economic growth across 18 Latin American countries from 1980 to 2010. Granger causality tests indicate that renewable electricity consumption plays a more substantial role in boosting output than its non-renewable counterpart. Shahbaz et al. (2015) employ an auto-regressive distributed lag (ARDL) method to explore the connection between renewable energy consumption and economic growth in Pakistan from 1972 to 2011. Inglesi-Lotz (2016) analyzed the impact of renewable energy consumption and its proportion in the total energy mix on economic growth in OECD countries, finding a positive and statistically significant effect. Bhattacharya et al. (2016) extend the analysis to 38 top renewable energy countries, while Paramati et al. (2017) focus on the role of renewable energy in economic growth for the Next 11 developing countries from 1990 to 2012.

Jebli and Youssef (2015) integrated international trade into their production function, examining the effects of capital, labor, renewable, and non-renewable energy on output for 69 countries from 1980 to 2010. OLS, DOLS, and FMOLS results suggest that the elasticity estimate of renewable energy is approximately 4%. Halicioglu and Ketenci (2018) employed the same production function for EU-15 countries from 1980 to 2015, using both ARDL and GMM methods. Their findings reveal that renewable and non-renewable energy affect output differently in each country. In the context of examining the links between renewable energy use and economic growth in developing countries, Ben Mbarek et al. (2018) provide valuable insights into the relationship between these two critical factors. Their study, focused on Tunisia, demonstrates the significant role that renewable energy consumption plays in fostering economic growth. By utilizing advanced econometric techniques, they show a positive and long-term association between renewable energy use and economic performance, which highlights the importance of transitioning to cleaner energy sources for sustainable development in emerging economies. This research underscores the broader implications for other developing nations aiming to enhance growth while minimizing environmental impacts.

In response to growing environmental concerns, a body of research integrates the analysis of the interplay among three variables: growth, energy, and pollution. Noteworthy investigations employing this approach include studies by Soytas et al. (2007), Akbostanci et al. (2009), Soytas & Sari (2009), Zhang & Cheng (2009), Jalil & Mahmud (2009), Ozturk & Acaravci (2010), Apergis & Payne (2010, 2014), Alam et al. (2011), and others. For instance, Izyan et al. (2013) examined the causal links between energy consumption, economic growth, and CO2 emissions in three Association of Southeast Asian Countries (ASEAN) nations like Malaysia, Indonesia, and Singapore during 1975-2011. Results varied across countries. In Malaysia, two unidirectional causal relationships were identified: from CO2 emissions to energy consumption and from energy consumption to economic growth. In Indonesia, economic growth caused CO2 emissions, while energy caused growth. In Singapore, no causal relationship among the three variables was observed.

Arouri et al. (2012) investigated the Environmental Kuznets Curve (EKC) in 12 Middle East and North Africa (MENA) countries from 1981 to 2005. They found that the EKC was not validated, concluding that MENA countries cannot reduce CO2 emissions without slowing down economic growth. Through unit root and panel cointegration tests, they established a significantly positive long-term impact of energy consumption on CO2 emissions for the entire region. The relationship between growth and CO2 emissions was identified as quadratic. Alam et al. (2011) studied the causal links among energy consumption, carbon dioxide (CO2), and income in India from 1971-2006. Their results indicated a long-term bidirectional relationship between energy consumption and CO2 emissions. However, the relationship was neutral between income and both energy consumption and CO2 emissions. Wang et al. (2011) affirmed the existence of causal relationships between economic growth, energy consumption, and CO2 emissions in their study of 28 Chinese provinces from 1995 to 2007. Using a Vector Error Correction Model (VECM), they identified bidirectional relationships between CO2 and energy, as well as between growth and energy, in the short term. In the long term, energy and growth influenced CO2 emissions, and vice versa.

Al-Mulali (2011) demonstrated, in a study covering the Middle East and North Africa (MENA) countries from 1980-2009, a long-term relationship between CO2 emissions, oil consumption, and economic growth. Short-term results revealed a bidirectional relationship among CO2, oil consumption, and economic growth. Apergis & Payne (2010) focused on 11 Commonwealth countries during 1992-2004, studying the causal links between energy consumption, real GDP and CO2 emissions. In the short term, bidirectional relationships existed between energy consumption and real GDP, and two unidirectional relationships from real GDP to CO2 emissions and from energy consumption to CO2 emissions. In the long term, a bidirectional relationship between energy and CO2 was identified. Additionally, the relationship between real GDP and CO2 exhibited an inverted "U" shape, with CO2 emissions initially increasing with real GDP and then decreasing after reaching a certain threshold. In the context of developing and emerging economies, our literature review reveals a notable gap in research. The existing studies predominantly focus on major Asian economies, particularly China and Pakistan, as well as Latin American countries. However, limited attention has been directed toward emerging petroleum nations, particularly those in the Middle East, such as Saudi Arabia.

2. OVERVIEW ON ENERGY SECTOR IN SAUDI ARABIA

Saudi Arabia, historically recognized for its extensive oil reservoirs and impact on worldwide petroleum markets, faces the urgent need to shift towards more eco-friendly energy sources amid the critical challenges posed by climate change. The global trend is leaning towards cleaner energy solutions to mitigate greenhouse gas emissions and address the issue of global warming. Against this backdrop, it becomes crucial for the kingdom to assess and channel investments into viable sustainable energy alternatives.

Saudi Arabia is one of the world's largest oil producers and exporters, and the oil and natural gas energy sector forms the backbone of the national economy. This sector plays a crucial role in determining the Kingdom's economic growth paths. This topic addresses the role of the energy sector in economic growth in the Kingdom of Saudi Arabia and the efforts made by the government to promote economic diversification and achieve sustainable development. In fact, the Kingdom of Saudi Arabia is considered one of the largest oil producers and exporters in the world, and possesses huge reserves of oil and natural gas. The energy sector plays a vital role in the Kingdom's economy. Oil is a major source of national revenue. The Kingdom is working to diversify its energy sources, and is investing in areas such as solar and wind energy. There is a shift towards using renewable energy sources to meet growing electricity needs. The Kingdom is investing in major projects in the energy field, including the NEOM project, which aims to develop a special economic zone for energy, technology and sustainability.

The Saudi Kingdom's reliance on gas for electricity generation has become increasingly significant. In 2017, over 64% of its electricity was generated from natural gas, with only 36% from oil—a share that has sharply declined. Due to the gradual development of its renewable energy sector, Saudi Arabia is actively working on enhancing both its conventional and unconventional gas production. The Kingdom has set an ambitious goal of doubling its total production within the next ten years. Unlike the UAE, Saudi Arabia meets its domestic gas consumption needs through its own production, which amounted to 112 Gm3 in 2018. Furthermore, it aspires to become a net exporter. Despite this declared intention, uncertainties persist regarding Saudi Arabia's ability to export gas in the coming decades. Both the UAE and Saudi Arabia share a common objective of diversifying their energy mix by harnessing alternative energies. They aim to capitalize on the region's vast potential in renewable energies, particularly solar power. This move signifies a strategic effort to reduce dependence on traditional energy sources and align with global trends in sustainable and environmentally friendly energy production.

3. METHODOLOGY AND RESULTS

Our objective in this paper is to determine the dynamic links between renewable energy consumption, industry evolution, economic growth and pollution for Saudi economy during 1990-2019 using granger causality tests based on VECM model and supported by unit-root tests and co-integration. In addition, VECM is an extension of the Vector Auto-regression (VAR) model which makes it possible to model co-integration relationships between several time series (variables). It is particularly useful when the time series are non-stationary and exhibit a long-term relationship. The VECM model begins with a VAR model that captures short-term relationships between variables. A p-order VAR model specifies how each variable depends on its own lags and the lags of other variables.

$$Y_t = \alpha + \sum_{i=1} pA_i Y_{t-1} + \varepsilon_t$$

where Y_t is the vector of endogenous variables at the time (t). The matricesA_i are the coefficients, α is the intercept vector, and ε_t the error vector for each model. VECM includes the possibility of co-integration between variables, meaning that there is a stable long-term relationship between these variables. This is detected by the Engle-Granger test or the Johansen test. VECM incorporates co-integration errors through error correction terms. These terms adjust short-term variables toward their long-term equilibrium.

3.1 Descriptive statistic

Table 1 present the annual data used in this the paper which are taken from the World Development Indicator (WDI, 2022-CD-ROM) for Saudi Arabia, and cover 1990–2019. The analyzed variables are: the economic growth (measured by Gross Domestic Product Growth Per capita, annual %), globalization (GLI) measured by index, CO2 emissions (measured in metric tons per capita), energy use (EU) (measured in kilogram (kg) of oil equivalent per capita), and Renewable energy consumption RE by % of total final energy consumption (measured in 1000 metric tons of oil equivalent). In fact, the descriptive statistics for the variables in this study provide valuable insights into their central tendencies, variability, and distributional characteristics, essential for understanding the underlying data patterns. The mean CO2 emissions per capita stand at 13.32 metric tons, with a median of 12.80, indicating a slight positive skewness (0.43) and moderate variability (standard deviation of 2.12). The distribution is relatively flat, as evidenced by the kurtosis of 1.73, and does not significantly deviate from normality, as shown by the Jarque-Bera test (p = 0.227). Energy consumption per capita (EC) exhibits a mean of 99.88 kg of oil equivalent, with a median close to this value (99.99), indicating a nearly symmetrical distribution. However, it is significantly negatively skewed (-1.86) with very low variability (standard deviation of 0.24) and a leptokurtic distribution (kurtosis of 5.04). The Jarque-Bera test confirms a significant deviation from normality (p = 0.00001).

The economic growth variable (GDPGPC) has a mean of 0.79%, with a median substantially lower at 0.27%, highlighting a positive skew (0.66). This variable exhibits substantial variability, as indicated by the standard deviation of 4.47%, and a distribution that is approximately normal (kurtosis of 2.90), with no significant deviation from normality (p = 0.33). Industrial activity (IND) presents a mean of 3.24, with a median of 2.57, indicating positive skewness (1.22) and significant variability (standard deviation of 7.18). The distribution is leptokurtic (kurtosis of 4.35) and deviates significantly from normality ($p = 0.0077$).

Renewable energy consumption (RE) is characterized by a very low mean (0.0146) and median (0.01000), with a strong positive skewness (1.76) and low variability (standard deviation of 0.0093). The distribution is sharply peaked (kurtosis of 4.64) and significantly deviates from normality ($p = 0.00008$). Finally, the globalization index (GLI) shows a mean of 0.1059 and a median of 0.0886, indicating moderate positive skewness (0.75) and variability (standard deviation of 0.0604). The distribution is nearly normal (kurtosis of 2.99) and does not significantly deviate from normality ($p = 0.24$). Collectively, these statistics underscore the variability and distributional characteristics of the data, providing a foundational understanding for subsequent analyses in the context of the study's focus on economic growth, globalization, environmental impact, and energy consumption. The descriptive statistics Mean, Median, Maximum, and Minimum of these variables are recorded below in Table 1. The correlation test is also attached by this table. According the correlation test by table (1), starting with CO2 emissions (CO2), it shows a moderate positive correlation with energy consumption (EC) (0.525), indicating that higher energy consumption is associated with increased CO2 emissions. This relationship aligns with expectations, as greater energy use typically leads to more emissions. However, CO2 emissions have a weak positive correlation with GDP per capita growth (GDPGPC) (0.066), suggesting that economic growth is not strongly linked to changes in CO2 emissions in this context. Interestingly, CO2 emissions are weakly negatively correlated with industrial activity (IND) (-0.113), which may reflect efficiency improvements or shifts towards less carbon-intensive industries. The negative correlation between CO2 emissions and renewable energy consumption (RE) (-0.414) suggests that greater reliance on renewable energy sources tends to reduce CO2 emissions, highlighting the environmental benefits of renewable energy adoption. Finally, the correlation between CO2 emissions and the globalization index (GLI) is moderately negative (-0.597), implying that higher levels of globalization are associated with lower CO2 emissions, which might be due to increased access to cleaner technologies or stricter environmental regulations associated with globalization.

The energy consumption (EC) variable exhibits a very weak positive correlation with GDPGPC (0.117) and an almost negligible correlation with industrial activity (IND) (0.004). These weak correlations indicate that, within this dataset, energy consumption is not strongly driven by economic growth or industrial activity. The correlation between energy consumption and renewable energy consumption (RE) is also low (0.101), suggesting that the overall energy consumption levels are not heavily influenced by the share of renewables. However, there is a modest positive correlation between energy consumption and the globalization index (GLI) (0.325), indicating that more globalized economies tend to consume more energy, possibly due to increased economic activities linked to globalization.

GDP per capita growth (GDPGPC) has a strong positive correlation with industrial activity (IND) (0.968), indicating that economic growth in this context is closely tied to industrial expansion. This is a common finding in many economies where industrial output is a significant driver of GDP growth. The correlation between GDPGPC and renewable energy consumption (RE) is moderate (0.289), suggesting that economies with higher growth rates may also be increasing their use of renewable energy, although this relationship is not particularly strong. Additionally, the positive correlation between GDPGPC and the globalization index (GLI) (0.627) indicates that more globalized economies tend to experience higher economic growth, reflecting the benefits of globalization on economic expansion.

Industrial activity (IND) is strongly positively correlated with GDPGPC (0.968) and also shows moderate positive correlations with renewable energy consumption (RE) (0.449) and the globalization index (GLI) (0.669). These correlations suggest that industrial growth is associated with both economic growth and increased use of renewable energy, as well as higher levels of globalization, which could be due to industrial sectors benefiting from global markets and investments. Renewable energy consumption (RE) shows moderate positive correlations with industrial activity (IND) (0.449) and the globalization index (GLI) (0.675). This suggests that more industrialized and globalized economies are likely to adopt renewable energy sources. The relationship between renewable energy consumption and GDPGPC is weaker (0.289), but still positive, indicating that economic growth might be somewhat conducive to renewable energy adoption. Finally, the globalization index (GLI) is positively correlated with all the variables except CO2 emissions. The strongest positive correlations are with industrial activity (IND) (0.669) and renewable energy consumption (RE) (0.675), indicating that globalization is linked with industrial expansion and the adoption of renewable energy. The positive correlation with GDPGPC (0.627) further supports the idea that globalization promotes economic growth. The negative correlation with CO2 emissions (-0.597) suggests that globalization might contribute to reducing CO2 emissions, potentially through the diffusion of cleaner technologies and practices.

In summary, the correlation analysis reveals that industrial activity and globalization are key drivers of economic growth, with significant positive correlations across related variables. Renewable energy consumption is positively associated with industrialization and globalization, while CO2 emissions are negatively correlated with globalization and renewable energy use, highlighting the potential environmental benefits of these trends.

Table 1. Descriptive statistic and correlations between variables

	CO2	*EC*	*GDPGPC*	*IND*	*RE*	*GLI*
Mean	13.320	99.878	0.7933	3.2370	0.0146	0.1058
Median	12.798	99.995	0.2679	2.5747	0.0100	0.0885
Maximum	17.257	99.996	10.522	22.845	0.0400	0.2560
Minimum	10.709	99.203	-6.2234	-6.9587	0.0100	0.0150
Std. Dev.	2.1195	0.2404	4.4730	7.1835	0.0093	0.0604
Skewness	0.4322	-1.8552	0.6637	1.2193	1.7600	0.7546
Kurtosis	1.7277	5.0391	2.8983	4.3534	4.6354	2.9959
Jarque-Bera	2.9574	22.407	2.2154	9.7235	18.832	2.8477
Probability	0.2279	0.0000	0.3303	0.0077	0.0001	0.2407
Sum	399.61	2996.3	23.801	97.112	0.4400	3.1760
Sum Sq. Dev.	130.28	1.6760	580.23	1496.5	0.0025	0.1057
Observations	30	30	30	30	30	30
Correlation	CO2	EC	GDPGPC	IND	RE	GLI
CO2	1.0000	-	-	-	-	
EC	0.5252	1.0000	-	-	-	
GDPGPC	0.0657	0.1171	1.0000	-	-	
IND	-0.1128	0.0038	0.9679	1.0000	-	
RE	-0.4142	0.1006	0.2888	0.4486	1.0000	
GLI	-0.5968	0.3251	0.6265	0.6693	0.6754	1.0000

Source: own

3.2 Stationary analysis

We begin our empirical study by analyzing the stationarity of each variable and by applying the unit root tests at level and first difference (table (2)); first, we apply the Augmented Dickey Fuller (ADF) test introduced by Dickey & Fuller (1979). In practice, stationarity tests, including the Phillips & Perron (1988) (PP) test, are often used as a preliminary step in time series analysis before choosing an appropriate model. In fact, the optimal approach for ascertaining the integration order of a series relies on employing unit root tests. These tests are designed to identify the existence of a unit root within a series. Typically, two commonly utilized unit root tests include the ADF test, and the PP test.

Taking the ADF test on the CO2 series as an example, we express the test equation with the constant term, as well as the trend and intercept terms, as follows:

$$\Delta CO2_t = \alpha + \beta_t + \delta CO2_t + \sum_{i=1}^{k} \beta_i CO2_{t-i} + \varepsilon_t$$

where α, β, and δ are coefficients; ε is a residual term; and k is the lag length, which transforms the residual term into a stochastic variable. The null hypothesis H0 is $\delta = 0$; meaning that there is at least one-unit root, causing non-stationarity in the series. The test is conducted with three formulations: ($\alpha \neq 0$, $\beta \neq 0$), ($\alpha = 0$, $\beta \neq 0$), and ($\alpha = 0$, $\beta = 0$). The Unit root test presented in next table (2) confirms that all variables have the same degree of integration (are stationary in first difference).

Table 2. Unit root tests

Variables	*Level*		*1st Difference*	
	(i)	(ii)	(i)	(ii)
		ADF Test		
CO2	6.6435	-2.4231	*-4.8998**	*-3.1011***
EC	-0.4477	-1.4374	*-5.0320**	*-4.8835**
GDPGPC	1.7320	-0.3742	*-3.6748**	*-4.4378**
IND	3.3443	-0.9669	*-4.2721**	*-6.3627**
RE	1.9666	-2.1325	*-2.7598**	*-3.7179***
GLI	0.7326	*-4.448927*	*-4.132565**	*-4.8838**
		PP test		
CO2	5.4596	-2.4231	*-4.8938**	*3.8808***
EC	-0.3114	-1.4374	*-5.0350**	*-4.8865**
GDPGPC	3.7622	0.7243	*-3.6790**	*-4.5698**
IND	5.9720	-1.4528	*-4.2843**	*-9.1356**
RE	1.9066	-2.1366	*-2.6980**	*-2.9135**
GLI	0.7456	-4.3565	*-4.8656**	*-4.6958**

Note: Without constant, (ii): with a constant. * and **: asterisks denote p-value less than 1% and 5%. Critical levels in the model: (i) -2.60 (1%) and -1.95 (5%).
Source: own

3.3 Co-integration analysis

The Toda and Yamamoto Granger causality analysis does not necessitate the existence of co-integration. However, for the examination of long-run estimates using the VECM model, the presence of co-integration becomes essential. The Johansen co-integration test employs trace statistics and max-eigenvalue statistics, with the null hypothesis requiring rejection at a 5% significance level to confirm long-run co-integration among variables. The equation for the Unrestricted Cointegration Rank Test (Trace) is as follows:

$$\lambda_{trace}(r) = -T\sum_{i=r+1}^{k} \ln(1-\hat{\lambda}_i)$$

The trace statistic, denoted as $\lambda_{trace}(r)$, tests the null hypothesis that there are at most (r) cointegrating vectors among the variables. In this context, T represents the number of observations, while $\hat{\lambda}_i$ refers to the estimated eigenvalues, also known as characteristic roots, derived from the model's estimation. The test is conducted for different values of (r), ranging from $(r = 0)$ to $(r = k - 1)$, where (k) is the total number of variables in the system. The null hypothesis H_0 asserts that there are at most (r) co-integrating relationships within the dataset.

Table 3 reveals that both trace and max-eigenvalue tests signify 1 and 2 co-integration relationships, respectively, among the selected variables at a 5% significance level. In fact, The Unrestricted Cointegration Rank Test (Trace) indicates a strong long-term relationship among the variables CO2 emissions, energy consumption (EC), GDP per capita growth (GDPGPC), industrial activity (IND), renewable energy consumption (RE), and globalization index (GLI). The test rejects the null hypothesis of no cointegration at the 5% significance level for up to three cointegrating equations. Specifically, the trace statistics for the first three ranks are 102.32, 55.529, and 31.458, each exceeding their respective critical values, with associated p-values of 0.0000, 0.0081, and 0.0319. This suggests that there are up to three cointegrating relationships among these variables, indicating a stable and long-run equilibrium among them.

The identification of long-run co-integration lends support to the assertion of Granger causality between the variables.The co-integration test solely indicates the existence of Granger causality among the chosen variables without specifying the direction of this causal relationship. Subsequent tests were employed to investigate the causality among the selected variables.

Table 3. Co-integration test

Unrestricted Cointegration Rank Test (Trace)				
Hypothesized No. of CE(s)	Eigenvalue	*Trace Statistic*	*Critical Value (0.05)*	*Prob.***
None *	0.8120	102.32	69.818	0.0000
At most 1 *	0.5766	55.529	47.856	0.0081
At most 2 *	0.5117	31.458	29.797	0.0319
At most 3	0.3029	11.382	15.494	0.1890
At most 4	0.0445	1.2763	3.8414	0.2586

Note: Trace test indicates 3 cointegrating equ(s) at the 0.05 level, * denotes rejection of the hypothesis at the 0.05 level, **MacKinnon-Haug-Michelis (1999) p-values
Source: own

3.4 VAR Lag Order Selection Criteria

The number of lags to include in a vector autoregressive (VAR) model depends on several factors, including the structure of the data, the complexity of the underlying system, and the modeling objectives. In general, to determine the optimal number of lags in a VAR model, several approaches can be used. In fact, the lag length selection criteria indicate that one lag is optimal for estimating the VAR and VECM models, as evidenced by multiple measures: the LR test shows the highest statistic at lag 1 (102.7370), the FPE is minimized at one lag (4.92e-06), and both the SC (3.368706) and HQ (2.357021) criteria also reach their lowest values at this lag. Although the AIC reaches its minimum at lag 3, it still shows a notably low value at lag 1 (1.928887). The consistency across these criteria suggests that using one lag is appropriate for capturing the dynamics among the variables CO2, energy consumption (EC), GDP per capita growth (GDPGPC), industrial activity (IND), and renewable energy consumption (RE), balancing model complexity with explanatory power for robust and reliable results.

Table 4. VAR model

Endogenous variables: CO2 EC GDPGPC IND RE						
Lag	LogL	LR	FPE	AIC	SC	HQ
0	-62.085	NA	9.90e-05	4.9692	5.2092	5.0406
1	***3.9600***	***102.73****	***4.92e-06****	***1.9288***	***3.3687****	***2.3570****
2	22.655	22.157	9.71e-06	2.3958	5.0355	3.1808
3	54.753	26.154	1.09e-05	1.8700*	5.7096	3.0117

Note: * indicates lag order selected by the criterion, LR: sequential modified LR test statistic (each test at 5% level), FPE: Final prediction error, AIC: Akaike information criterion, SC: Schwarz information criterion, HQ: Hannan-Quinn information criterion.
Source: own

3.5 Causality analysis based on VECM model

In the Granger sense, one time series "causes" another series if knowledge of the history of the first improves the prediction of the second. According to Sims (1980), a series can be recognized as causing another series if the innovations in the first contribute to the variance of the forecasting error in the second. Since the development of this statistical hypothesis test, some studies on the properties of various testing methods have been published, such as Belloumi (2009), Mantalos and Shukur (2010), Sung and Song (2013), BenMbarek et al (2016) and Koondhar et al (2021).

The mathematical representation of Granger causality can be formulated using autoregressive (AR) models. Let's assume we have the following AR models:

$$Y_t = \alpha + \sum_{i=1}^{p} \beta_i Y_{t-i} + \sum_{j=1}^{q} \gamma_i X_{t-j} + \epsilon_t$$

$$X_t = \delta + \sum_{k=1}^{r} \mu_k X_{t-k} + \sum_{l=1}^{s} \emptyset_l X_{t-l} + v_t$$

In these equations, the coefficients $\gamma_j$and $\emptyset_l$ measure the impact of the delays of X and Y respectively on the current values of Y and X.

- $\Delta GDPGPC_t = \alpha_1 ECT_{t-1} + \sum_{k=1}^{p-1} \beta_{11k} \Delta GDPGPC_{t-k} + \sum_{k=1}^{p-1} \beta_{12k} \Delta EC_{t-k} + \sum_{k=1}^{p-1} \beta_{13k} \Delta RE_{t-k} + \sum_{k=1}^{p-1} \beta_{14k} \Delta IND_{t-k} \sum_{k=1}^{p-1} \beta_{15k} \Delta CO2_{t-k} + \sum_{k=1}^{p-1} \beta_{16k} \Delta GLI_{t-k} + \mu_{1t}$

- $\Delta EC_t = \alpha_2 ECT_{t-1} + \sum_{k=1}^{p-1} \beta_{21k} \Delta GDPGPC_{t-k} + \sum_{k=1}^{p-1} \beta_{22k} \Delta EC_{t-k} + \sum_{k=1}^{p-1} \beta_{23k} \Delta RE_{t-k} + \sum_{k=1}^{p-1} \beta_{24k} \Delta IND_{t-k} \sum_{k=1}^{p-1} \beta_{25k} \Delta CO2_{t-k} + \sum_{k=1}^{p-1} \beta_{26k} \Delta GLI_{t-k} + \mu_{2t}$

- $\Delta RE_t = \alpha_3 ECT_{t-1} + \sum_{k=1}^{p-1} \beta_{31k} \Delta GDPGPC_{t-k} + \sum_{k=1}^{p-1} \beta_{32k} \Delta EC_{t-k} + \sum_{k=1}^{p-1} \beta_{33k} \Delta RE_{t-k} + \sum_{k=1}^{p-1} \beta_{34k} \Delta IND_{t-k} \sum_{k=1}^{p-1} \beta_{35k} \Delta CO2_{t-k} + \sum_{k=1}^{p-1} \beta_{36k} \Delta GLI_{t-k} + \mu_{3t}$

- $\Delta IND_t = \alpha_4 ECT_{t-1} + \sum_{k=1}^{p-1} \beta_{41k} \Delta GDPGPC_{t-k} + \sum_{k=1}^{p-1} \beta_{42k} \Delta EC_{t-k} + \sum_{k=1}^{p-1} \beta_{43k} \Delta RE_{t-k} + \sum_{k=1}^{p-1} \beta_{44k} \Delta IND_{t-k} \sum_{k=1}^{p-1} \beta_{25k} \Delta CO2_{t-k} + \sum_{k=1}^{p-1} \beta_{46k} \Delta GLI_{t-k} + \mu_{4t}$

- $\Delta CO2_t = \alpha_5 ECT_{t-1} + \sum_{k=1}^{p-1} \beta_{51k} \Delta GDPGPC_{t-k} + \sum_{k=1}^{p-1} \beta_{52k} \Delta EC_{t-k} + \sum_{k=1}^{p-1} \beta_{53k} \Delta RE_{t-k} + \sum_{k=1}^{p-1} \beta_{54k} \Delta IND_{t-k} \sum_{k=1}^{p-1} \beta_{55k} \Delta CO2_{t-k} + \sum_{k=1}^{p-1} \beta_{56k} \Delta GLI_{t-k} + \mu_{5t}$

- $\Delta GLI_t = \alpha_6 ECT_{t-1} + \sum_{k=1}^{p-1} \beta_{61k} \Delta GDPGPC_{t-k} + \sum_{k=1}^{p-1} \beta_{62k} \Delta EC_{t-k} + \sum_{k=1}^{p-1} \beta_{6k} \Delta RE_{t-k} + \sum_{k=1}^{p-1} \beta_{64k} \Delta IND_{t-k} \sum_{k=1}^{p-1} \beta_{65k} \Delta CO2_{t-k} + \sum_{k=1}^{p-1} \beta_{66k} \Delta GLI_{t-k} + \mu_{6t}$

The Error Correction Term (ECT) reflects long-run causality; if the coefficient α_i is significant, it indicates that the variable adjusts in response to deviations from the long-run equilibrium. Meanwhile, the β_{ijk} coefficients capture short-run Granger causality, where their significance indicates whether the past values of one variable can help predict changes in another, thus revealing the presence of short-term predictive relationships among the variables.

Among the main results in Table 5, there is bidirectional causality between globalization and economic growth with a significance level of 5% at short run.

The Vector Error Correction Model (VECM) Granger causality results reveal a complex network of relationships among the examined variables, characterized by both unidirectional and bidirectional causality in the short and long run, with varying levels of statistical significance. These results provide a nuanced understanding of how energy consumption, economic growth, industrial activity, environmental impact, and globalization are interrelated in the context of Saudi Arabia's economic landscape.

In the short run, several unidirectional causal relationships emerge, each significant at different levels. Energy consumption (EC) exhibits a significant unidirectional influence on GDP per capita growth (GDPGPC) at the 5% level, emphasizing the critical role of energy in driving economic expansion. Furthermore, EC significantly influences renewable energy consumption (RE) and carbon dioxide emissions (CO2) at the 1% level, suggesting that increases in energy consumption lead to higher adoption of renewable energy and greater carbon emissions. This relationship underscores the tension between promoting economic growth through energy use and managing its environmental consequences.

Industrial activity (IND) also displays unidirectional causality, affecting GDPGPC and CO2 at the 5% () and 1% level, respectively. The significant influence of IND on GDPGPC highlights the importance of industrial sectors in boosting economic performance, while the strong link between IND and CO2 emissions points to the environmental challenges posed by industrial growth. These results indicate that as industrial activity intensifies, it not only drives economic growth but also contributes significantly to environmental degradation, necessitating careful management of industrial expansion to minimize its ecological impact.

Moreover, GDP per capita growth (GDPGPC) is found to unidirectionally cause changes in the globalization index (GLI) at the 1% level, indicating that economic growth in Saudi Arabia is a key driver of the country's increasing integration into the global economy. This finding suggests that as the economy grows, it becomes more interconnected with global markets, reflecting the influence of domestic economic performance on globalization trends.

In addition to these unidirectional relationships, bidirectional causality is observed between certain variables, signifying reciprocal interactions. The bidirectional causality between GDPGPC and EC in the short run, significant at the 5% level, suggests a reinforcing loop where energy consumption drives economic growth, and economic growth in turn increases energy consumption. This interdependence highlights the challenge of balancing energy demand with sustainable economic development. Similarly, the bidirectional causality between EC and IND at the 5% level underscores the dynamic interplay between industrial output and energy consumption, with each influencing the other. This relationship reflects the close connection between energy use and industrial activity, suggesting that energy policies must be aligned with industrial strategies to ensure sustainable growth.

In the long run, the VEC term indicates significant causality affecting GDPGPC and IND. The long-term causality running from the exogenous variables to GDPGPC is significant at the 1% level, indicating that GDPGPC is influenced by long-term equilibrium relationships with the other variables, such as EC, IND, and GLI. This finding suggests that sustainable economic growth in Saudi Arabia depends on the careful management of these variables over time. The significant long-run causality to IND at the 1% level implies that industrial activity is particularly sensitive to long-term changes in energy consumption, economic conditions, and possibly environmental regulations. This sensitivity indicates that industries may need to adapt to evolving economic and environmental landscapes to sustain their growth over the long term.

Overall, these results provide a comprehensive understanding of the intricate relationships between energy consumption, economic growth, industrial activity, environmental impact, and globalization in Saudi Arabia. The identified unidirectional and bidirectional causal links, significant at various levels, suggest that policymakers must carefully coordinate energy policies, industrial strategies, and globalization efforts to support sustainable economic growth while managing environmental impacts. This integrated approach is essential for achieving long-term development goals in the context of globalization and economic transformation.

Table 5. Short- and long-term results by VEC Granger causality

		Exogenous variables						
		Short run						Long run
		D(GDPGPC)	D(EC)	D(RE)	D(IND)	D(CO2)	D(GLI)	VEC
Exogenous variables	D(GDPGPC)	-	5.477** (0.0193)	1.6138 (0.2040)	4.3725** (0.0365)	2.4458 (0.1178)	8.213** (0.0165)	1.913*** [4.1245]
	D(EC)	5.685** (0.0171)	-	1.6679 (0.1965)	4.5343** (0.0332)	2.8317* (0.0924)	2.9882 (0.2244)	-0.01463 [-0.5432]
	D(RE)	0.3986 (0.5278)	14.916*** (0.0001)	-	0.1471 (0.7013)	10.31*** (0.0013)	20.931 (0.0000)	0.0135 [0.2881]
	D(IND)	0.3130 (0.5758)	1.3532 (0.2447)	0.0003 (0.9872)	-	0.432712 (0.5107)	1.7635 (0.4140)	3.2021*** [4.947]
	D(CO2)	0.1872 (0.6652)	14.836*** (0.0001)	0.0259 (0.8719)	10.732*** (0.0011)	-	1.2408 (0.5377)	0.0255 [0.5237]
	D(GLI)	11.47** (0.0032)	0.6712 (0.7149)	2.4471 (0.2942)	1.0139 (0.6023)	0.2420 (0.8860)	-	0.2078 [0.9576]

Note: H0 Rejected (***) the null hypothesis at 1% level, H0 rejected (**) the null hypothesis at 5% significant level, H0 Rejected (*) the null hypothesis at 10% level.
Source: own

3.6 Impulse response function

In the context of Granger causality, one can examine the impulse response function (IRF) to assess the response of one time series to a shock or impulse in another time series. However, it is important to note that the term "impulse response function" may be more frequently associated with linear dynamic systems and signal theory rather than Granger causality, which is typically based on statistical methods. In fact, the impulse response function (IRF) is an important concept in signal processing and systems theory. It describes the output of a system in response to a unit impulse, which is an idealized mathematical function that is zero everywhere except at a single point where it takes the value of 1.

The Kingdom is committed to promoting sustainability and environmental preservation in the energy sector, as it has an ambitious vision to achieve sustainable development and reduce carbon emissions. The Kingdom seeks to enhance innovation in the field of energy and use the latest technologies to improve oil and gas production and enhance the efficiency of energy consumption.

The Kingdom seeks to enhance international cooperation in the field of energy by establishing partnerships with international companies and participating in global projects to develop energy sources. The Kingdom of Saudi Arabia occupies an important position in the global energy market, and is trying to direct its attention towards achieving sustainable development and diversifying energy sources with the aim of maintaining the sustainability of its economy in the future.

Interpretation:

The Impulse Response Functions (IRFs) derived from the Vector Error Correction Model (VECM) offer a detailed view of how shocks to one variable influence the dynamics of other variables over time. Each response reflects the significance and duration of the impact, providing a deeper understanding of the relationships within the model, particularly in the context of Saudi Arabia's economic and environmental landscape.

Starting with the response of GDP per capita growth (GDPGPC) to a shock in energy consumption (EC), the impact is significant and positive, particularly in the early periods, before gradually declining as the system returns to equilibrium. This suggests that an increase in energy consumption initially boosts economic growth, but the effect diminishes after about five periods, reflecting a short-term boost that tapers off as the economy adjusts. The significance of this response, particularly in the first few periods, underscores the central role of energy in driving economic activity.

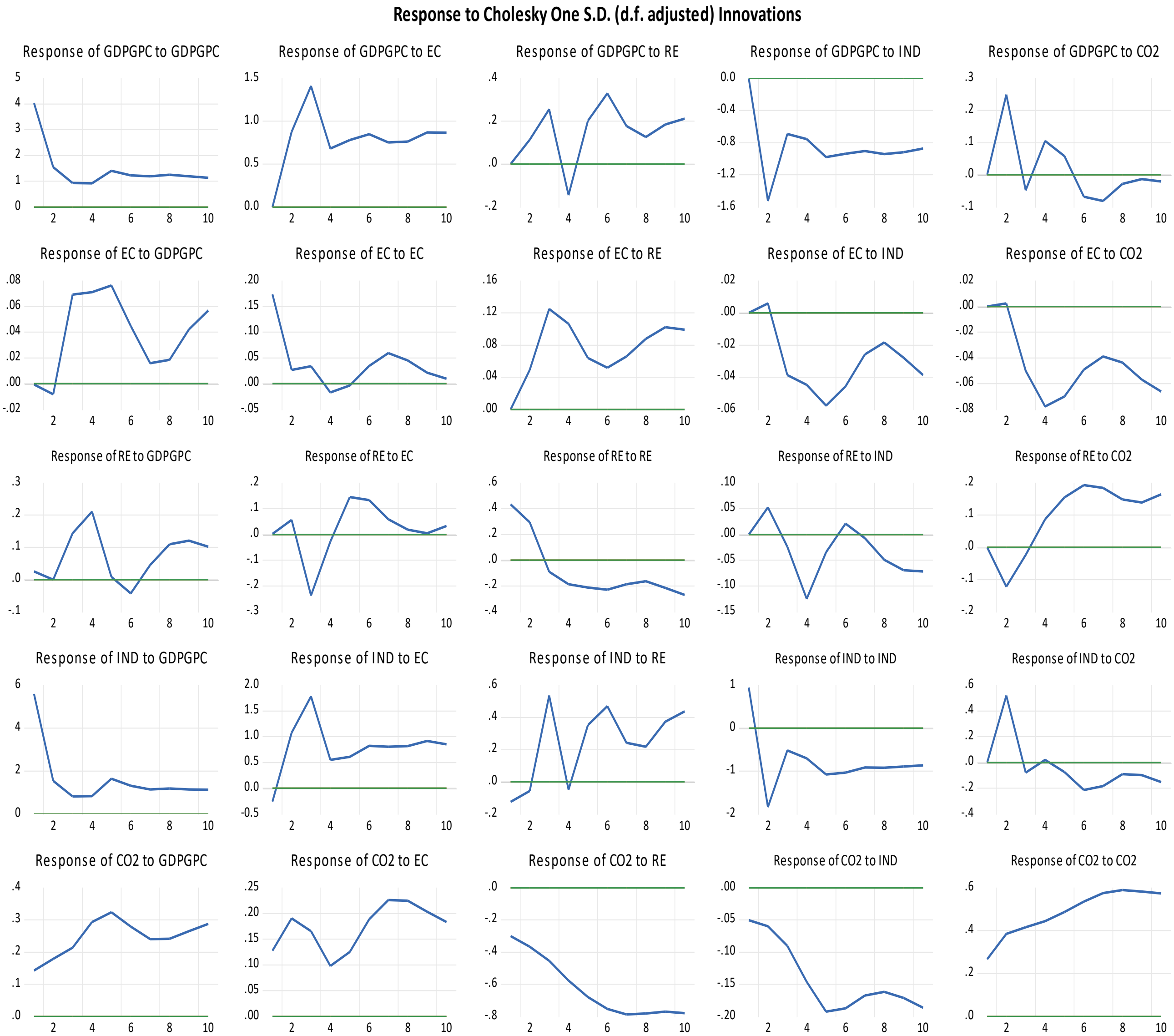

Figure 1. Impulse Response combined graphs (Cholesky One S.D. (d.f. adjusted)
Source: author's elaboration

The response of GDPGPC to a shock in renewable energy consumption (RE) is also noteworthy. Initially, there is a positive response, significant at the 5% level, indicating that renewable energy contributes positively to economic growth. However, this effect turns negative in subsequent periods before stabilizing, suggesting potential short-term inefficiencies or adjustment costs associated with the transition to renewable energy. The overall significance of this response highlights the complex relationship between economic growth and renewable energy, where initial benefits may be offset by transitional challenges.

In the case of industrial activity (IND), its shock leads to a positive and significant response in GDPGPC, particularly in the early periods. This indicates that industrial expansion significantly drives economic growth, but like the impact of EC, this effect diminishes over time, stabilizing after around four to five periods. The significance of this response, especially in the initial periods, reinforces the critical role of industrial sectors in shaping economic outcomes.

When examining the response of GDPGPC to a shock in CO2 emissions, the results are mixed. Initially, there is a positive response, significant at the 10% level, suggesting that economic activities contributing to CO2 emissions may temporarily boost growth. However, this effect quickly turns negative, highlighting the detrimental long-term impact of environmental degradation on economic performance. This response stabilizes after six to seven periods, indicating that the economy eventually adjusts, but the initial negative impact of higher emissions is significant.

The response of GDPGPC to a shock in the globalization index (GLI) is positive and sustained, particularly in the first few periods, where the impact is significant at the 5% level. This indicates that globalization has a lasting positive effect on economic growth, driven by increased trade, investment, and integration into global markets. The significance and persistence of this response suggest that as Saudi Arabia becomes more globally integrated, the benefits to economic growth are both substantial and enduring.

Turning to the response of EC to GDPGPC, the impact is significant and positive in the early periods, indicating that economic growth increases energy consumption. This response is particularly strong in the first three periods, after which it begins to stabilize. The significance of this relationship underscores the bidirectional causality between energy consumption and economic growth, where each reinforces the other.

The response of EC to a shock in RE is negative, especially in the first two periods, where the impact is significant at the 1% level. This suggests that an increase in renewable energy leads to a reduction in overall energy consumption, likely due to improved efficiency or substitution effects. This response stabilizes after three periods, reflecting the economy's adjustment to the increased use of renewables.

The response of EC to IND shocks is positive and significant, particularly in the first two periods. This indicates that industrial activity drives energy consumption, reinforcing the strong link between industrial output and energy demand. The response stabilizes after four periods, reflecting the steady state that the economy reaches after the initial shock.

The response of EC to a shock in CO2 emissions is more complex, with an initially negative and significant response, especially in the first two periods. This suggests that efforts to reduce emissions might involve decreasing energy consumption. However, the response stabilizes relatively quickly, indicating that the economy adjusts to these changes within three periods.

Finally, the response of renewable energy consumption (RE) to shocks in other variables, such as GDPGPC, EC, IND, CO2, and GLI, reveals a generally positive and significant impact, especially in the early periods. The response to GDPGPC is positive and significant, particularly in the first two periods, indicating that economic growth promotes the adoption of renewable energy. Similarly, the response to EC shocks is positive, suggesting that increased energy demand leads to higher renewable energy consumption. The response to IND shocks, though initially negative, becomes positive and significant after two periods, reflecting a shift towards more sustainable energy sources in industrial sectors. The positive response of RE to CO2 emissions, significant in the first three periods, highlights the role of renewables in mitigating environmental impacts. Lastly, the response of RE to GLI is positive and sustained, indicating that globalization facilitates the adoption of renewable technologies over time.

In summary, the Impulse Response Functions illustrate the dynamic interactions between key economic and environmental variables, with each response characterized by its significance level and duration. These results underscore the critical importance of energy consumption, industrial activity, and globalization in driving economic growth, while also highlighting the growing role of renewable energy in addressing environmental challenges. The varied response periods and levels of significance across the variables suggest a complex and interconnected economic system, where policy interventions must carefully balance the trade-offs between growth and sustainability.

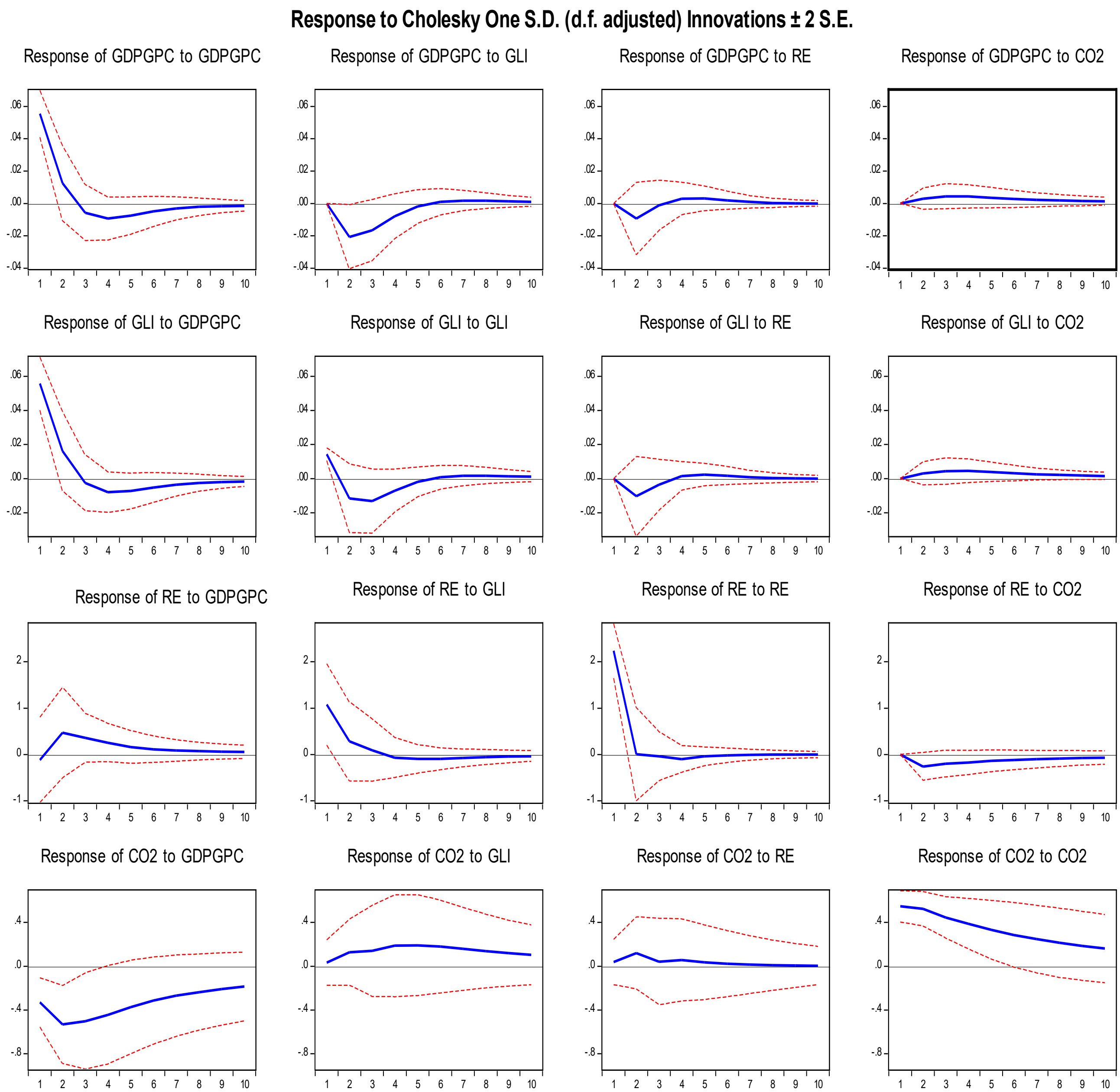

Figure 2. Impulse Response combined graphs (Cholesky One S.D. (d.f. adjusted)
Source: author's elaboration

The results displayed by the impulse response function *Figure 2* show that economic growth positively affects globalization in the short run; this effect disappeared after two periods. Globalization also has a positive and significant effect on the use of renewable energies in the short term. The estimation of the impulse response function confirms an important result, which describes that GDP negatively affects CO2 in the short and long term (i.e. 4 periods). Although GDP may initially be correlated with CO2 emissions, an economy can take steps to mitigate this relationship by adopting policies and technologies aimed at reducing emissions while supporting economic growth.

To overcome these challenges and realize the potential benefits of renewable energy for economic growth and pollution reduction, it is necessary to put in place coherent energy policies and financial incentives to encourage the adoption of clean energy. This can include subsidies for clean technologies, stricter emissions standards, carbon prices and investments in clean energy distribution infrastructure. Additionally, international cooperation is essential to address global challenges related to climate change and pollution, promoting the sharing of best practices, technologies and financial resources.

As a recommendation, the transition to renewable energy can play an important role in achieving economic growth while reducing pollution, but this requires globally coordinated action and concerted efforts to overcome technical barriers, economic and energy policies.

CONCLUSION AND RECOMMENDATIONS

The primary objective of this study was to explore the connection among globalization, renewable energy consumption, environmental pollution, and economic growth spanning the years 1990 to 2019. The stationarity of each variable was assessed using ADF and PP unit root tests. The Granger causality test also confirms the results using the impulse response function. The initial differencing rendered all variables stationary. Consequently, a Vector Error Correction Model (VECM) was employed to examine the cointegration between the series in both the short and long run. The main results show that there are bidirectional links between energy consumption and pollution, and between renewable energy consumption and economic growth.

A particularly promising option in this regard is green hydrogen. In fact, green hydrogen is indeed a very promising option for reducing CO2 emissions and promoting a more sustainable economy.

However, to become competitive with conventional hydrogen production methods, green hydrogen production still requires significant investments in infrastructure, technologies, and supporting policies, all of which are available in the Kingdom. However, with technological advancements and a growing commitment to the energy transition, green hydrogen is certainly an option to closely monitor in order to decarbonize our economy.

The results of the VECM estimation, supported by the impulse response function, confirmed that globalization contributes to economic growth, and vice versa. Globalization can serve the green economy in several ways, including technology transfer, trade in green goods and services, sustainable investments, international standards and regulations, international collaboration, and the sharing of best practices. In summary, globalization can play a crucial role in promoting the green economy by fostering innovation, trade, investment, and collaboration on a global scale to address the environmental challenges we face.

The Impulse Response Functions (IRFs) derived from the VECM offer critical insights into the dynamic relationships between key economic and environmental variables in Saudi Arabia. The findings highlight the significant but transient positive impact of energy consumption on GDP per capita growth, underscoring the central role of energy in driving economic activity. However, the diminishing effect over time suggests the need for strategies that sustain growth beyond the initial energy-driven boost. The complex relationship between renewable energy consumption and economic growth, where short-term benefits are offset by transitional inefficiencies, indicates that careful management of the renewable energy transition is crucial to minimize adjustment costs. Additionally, the positive and significant response of GDP to industrial activity reaffirms the industrial sector's pivotal role in economic development, though its energy demands necessitate balanced policies to mitigate environmental impacts. The mixed effects of CO2 emissions on economic growth further emphasize the importance of sustainable practices to avoid the long-term detrimental effects of environmental degradation. Finally, the sustained positive impact of globalization on economic growth underscores the importance of continued global integration for Saudi Arabia's economic future. Based on these insights, policymakers should focus on sustaining long-term economic growth through balanced energy policies, strategic management of the renewable energy transition, and continued global integration, while also addressing the environmental challenges associated with industrial expansion and energy consumption. These strategies will be crucial in achieving the broader goals of Saudi Arabia's Vision 2030, ensuring both economic prosperity and environmental sustainability.

Following the positive and significant impact of globalization in both economic growth and renewable energy use for Saudi context, this study highlights this positive and significant impact of globalization on economic growth and renewable energy use in Saudi Arabia, while also revealing the critical role of industrial activity in driving nonrenewable energy consumption. Policymakers should leverage globalization through trade liberalization, technology investment, and international collaborations to sustain economic growth, integrating these strategies with environmental sustainability initiatives. Simultaneously, addressing the significant energy demands of industrial activity is crucial for transitioning toward more sustainable energy practices. By investing in renewable energy infrastructure and fostering global partnerships, Saudi Arabia can position itself as a leader in regional sustainability efforts, contributing to the broader goals of Vision 2030. Future research should explore the impact of globalization and industrial activity on other sectors, consider the role of digitalization, and analyze the long-term causal relationships in different contexts. Ultimately, this study underscores that when effectively harnessed, globalization, alongside careful management of industrial energy consumption, can drive both economic prosperity and sustainable energy practices, offering valuable insights for other emerging economies.

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