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The dynamic relationships between oil products consumption and economic growth in Saudi Arabia: Using ARDL cointegration and Toda-Yamamoto Granger causality analysis

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A B S T R A C T

The purpose of this study is to investigate the short-run and long-run relationship between liquefied petroleum gas Consumption (LPGC), natural gas consumption (NGC), other refined products consumption (ORPC), carbon dioxide emissions (CO2), and gross domestic product (GDP) in Saudi Arabia, from 1970 to 2021. To study the link between energy consumption and economic growth and its role in this relationship, we use an autoregressive distributed lag (ARDL) bounds-testing technique of cointegration. The research findings revealed the development of a cointegrating association among all the variables. The anticipated results provide more evidence that a long-run link exists between the drivers of economic development and its regressors. The empirical estimation suggests an LPGC effect that is both beneficial and statistically significant on economic growth. A positive correlation exists between energy consumption and GDP growth. Using the Toda-Yamamoto Granger Causality approach, the causality test reveals a unidirectional causal relationship between the consumption of liquified petroleum and GDP, and between the consumption of natural gas and other refined products. In addition, there is bidirectional causality between GDP and other refined products. Consumption of natural gas and carbon dioxide emissions both have a neutral causal effect on economic growth. In the short run, NGC, ORPC, and CO2 have a positive effect on GDP. The KSA energy policy, actively engaged in slowing CO2 while preserving energy consumption, will significantly benefit from the conclusions of this research. Thus, policymakers should consider how to make LPGC, NGC, and ORPC more prudent and effective, particularly in the energy sector. The government of Saudi Arabia also needs to centralize the renewable energy sector.

1. Introduction

Energy is the driving force behind the global economy and a crucial component in the production of almost all of the goods and services available in the contemporary world [1]. Throughout the past several years, energy has been one of the speediest production factors, so it provides a significant impetus toward meeting sustainable development goals. Energy and the services it provides are essential to advancing health (quality of life), economic growth, and human flourishing [2]. There has been a lot of focus in economics research on the correlation between increased energy use and industrial development. Both energy and environmental sustainability can benefit from a deeper

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comprehension of the connection that exists between energy use and GDP. In Saudi Arabia, the primary goal of Vision 2030 is to diversify the economy by making the most of all available resources and clean technology. Saudi Arabia has an abundance of oil reserves, particularly petroleum. Long-term development in Saudi Arabia is guided by the Saudi Vision 2030, which aims to create a dynamic society and a strong economy in a forward-looking country. Alongside the aim of achieving economic diversification, environmental sustainability, and climate change have become increasingly important considerations in Saudi Arabia's energy policy. Hydrogen's capacity to lead the market, together with a carbon-neutral economy and sustainable use of hydrocarbons are some of the new programs that are being led by the Ministry of Energy and coordinated by energy-related institutions through an energy ecosystem [3]. In contrast to the previous year, 2021 saw a reduction in the level of uncertainty associated with cyber threats. The country's initiatives in this particular field directly contributed to this development. The leaders' primary focus, on an ongoing basis, to achieve the milestones outlined in the vision is on these action priorities. Saudi Arabia took the lead in carbon emissions management in 2020, when it held the G20[1] presidency, by illustrating the structure of cyclical decarbonization to aid in the worldwide transition to the utilization of sustainable energy. The Saudi Arabian government has made significant R&D investments and taken the lead in developing technologies to facilitate an ecosystem in which carbon dioxide emissions are reduced, recycled, reused, and removed (4 Rs), thereby preventing the release of carbon dioxide and other gases that cause climate change, while also generating economic value and fostering ecological sustainability. From 1968 until 2021, the Gross Domestic Product (GDP) of Saudi Arabia had an annual average of 274.12 billion US dollars, reaching an all-time high of 833.54 billion US dollars in 2021 and a record low of 4.19 billion US dollars in 1968. The General Authority for Statistics released data in 2022 that showed the Saudi economy achieved an increase in its gross domestic product (GDP) of 8.7 %, the highest growth rate among the G20 countries. Despite the global economic challenges and difficult conditions, the Saudi economy managed to achieve this.

By introducing the objectives of the Saudi Green Initiative (SGI), the Kingdom of Saudi Arabia has demonstrated its continued commitment to preserving the natural world and addressing the effects of climatic variability. The Middle East Green Initiative, in which the Kingdom is actively involved, plays a pivotal role in the region's efforts to combat and adapt to climate change. This initiative, which brings together regional leaders, aims to reduce the impacts of climate change for the benefit of the region's residents. Saudi Arabia's energy policies directly impact the safety and reliability of the international energy market. The Kingdom has consistently demonstrated that it is committed to ensuring market stability and maintaining energy supply safety and security. With a creative, dynamic, and participative approach, the country's energy policies have been swiftly developing, boosting the ecosystem's energy and dynamism. This strategy takes into consideration the management of climate change as well as economic diversification and environmental sustainability.

One of the most important challenges in the study of energy economics has been to gain a better understanding of the correlation between energy usage and economic expansion, including the question of whether growth causes energy consumption or the other way around. Within the study of energy economics, the hypothesis of a causal connection between the rising consumption of energy and growing economies has been the subject of a significant amount of research. Regarding causality's direction and its consequences (long-term versus short-term) for energy policy, the majority of the already obtained empirical evidence is inconsistent and presents inconsistent findings. This also holds for most of the existing findings. Because causality already exists, these relationships can have profound implications for one another.

Since the 1970s, while Kraft and Kraft [4] investigated the causal correlation between energy use and economic growth in the USA, the nexus between the consumption of energy and economic growth has been the subject of academic research. But disagreement persists. The preliminary research that Kraft and Kraft [4] conducted on the topic demonstrated a chain of causality that ran from income to energy consumption in the United States. The chain started with income and ended with energy consumption. These findings suggested that implementing energy policies could not harm economic endeavors. Several academics have replicated the Krafts' research, conducting experiments and uncovering diverse causality paths in several emerging nations. A causality chain that runs from energy consumption to income is indicative of an energy-dependent economy. In such an economy, a lack of energy would have a negative impact on income should there be a shortage of energy. A relationship running in the other direction, from income to energy consumption, would indicate the opposite situation. The economy's low reliance on energy allows for the adoption of conservation and efficiency policies without significant impact on output. Given the limited reliance on energy, this would be an economic way in which regulations aimed at conserving energy might be enforced.

The relationship between CO2 emissions, economic growth, and energy consumption is complex and multifaceted. On one hand, economic growth and increased energy consumption often lead to higher CO2 emissions due to greater industrial activity, transportation demands, and energy production. Environmental degradation, climate change, and health hazards contribute to this negative aspect. On the other hand, there are also positive aspects to consider. Economic growth, fueled by increased energy consumption, can lead to technological advancements and innovations in clean energy technologies, potentially reducing emissions per unit of economic output. Additionally, investments in renewable energy sources and energy efficiency measures can stimulate economic development while simultaneously mitigating CO2 emissions. However, it's crucial to recognize that the balance between economic growth and environmental sustainability is delicate. Unchecked growth and unsustainable energy consumption can exacerbate environmental degradation and pose long-term risks to economic stability and human well-being. Therefore, addressing this relationship requires a holistic approach that prioritizes sustainable development goals, promotes green technologies, and implements policies to decouple economic growth from carbon emissions.

This study's objective is to study the link that exists between energy consumption and economic growth. This study specifically focuses on the concepts of stationarity, cointegration, and causal direction. The need to synthesize existing literature on the link between energy consumption and economic growth motivated this research. It provides a systematic overview of the existing empirical literature on the relationship between energy use and GDP growth. Moreover, this paper seeks to enlarge current research in this field by investigating the effects of LPG consumption, natural gas consumption, CO2 emissions, and other refined product consumption (ORPC) on the environment-energy-growth link, with a focus on the KSA economy from 1970 to 2021. Taking into account the central role played by LPGC, NGC, ORPC, and CO2, we are unaware of any previous attempt to investigate this connection for the KSA. This article makes an effort to close that gap. To do so, we will employ an empirical approach built on two central tenets: To get started, we will analyze the long-run and short-run-term connections by employing the autoregressive distributed lag (ARDL) bounds testing technique of cointegration. The Vector Error Correction Model forms the basis for our next step, the Granger causality test (VECM). Among the goals of this research is to establish whether or not the variables under investigation are stationary or cointegrated and to

[1] The G20 is an international forum for the heads of state include both developed and developing countries. Members of the Group of Twenty (G20) account for roughly 80 % of global GDP, Three-quarters of global trade and two-thirds of the world's people live in Asia. G20 members meet regularly throughout the year to discuss economic and social matters.

analyze the direction of the causal connections between the consumption of energy and the growth of the economy.

The topic is especially relevant in the context of Vision 2030, Saudi Arabia's ambitious strategic framework aimed at diversifying the economy and reducing its heavy reliance on oil revenues. By exploring the dynamic relationship between oil consumption and economic growth, our study aims to provide critical insights that can inform these diversification efforts, ensuring they are based on a robust understanding of current economic dependencies. Moreover, the topic is significant on a global scale. Saudi Arabia is a leading oil producer, and changes in its oil consumption patterns and economic growth trajectories can have far-reaching implications for global oil markets, energy security, and economic stability. Therefore, our study not only addresses national policy concerns but also contributes to the international discourse on energy economics and sustainable development. From an academic perspective, there is a considerable gap in the literature regarding the specific dynamics of oil consumption and economic growth in Saudi Arabia. Existing studies often focus on broader regions or other oil-producing countries, leaving a critical need for country-specific analyses that can capture the unique economic and policy context of Saudi Arabia. Our research, by employing advanced econometric methods such as ARDL cointegration and Toda-Yamamoto Granger causality, provides a methodologically robust analysis that fills this gap and sets a benchmark for future studies. In summary, the choice of this topic is justified by its national and global relevance, its alignment with crucial economic policy initiatives, and its contribution to addressing significant gaps in the academic literature. Our study aims to provide both theoretical advancements and practical policy recommendations that are essential for guiding Saudi Arabia's economic future and contributing to broader understandings of the relationship between energy consumption and economic growth. Our study holds significant value for both academic research and policy-making in Saudi Arabia. By examining the dynamic interactions between oil consumption and economic growth, our findings provide crucial insights into how fluctuations in oil usage impact the broader economy. Given Saudi Arabia's reliance on oil as a primary economic driver, understanding these relationships is essential for informed policy decisions, particularly in the context of economic diversification and sustainable growth initiatives like Vision 2030. Additionally, the use of advanced econometric techniques such as ARDL and Toda-Yamamoto Granger causality ensures robust and reliable results, contributing to the existing literature by offering a methodologically sound analysis that can serve as a reference for future research in similar contexts. Thus, our paper not only fills a critical gap in the empirical literature but also provides practical implications for economic planning and policy formulation in oil-dependent economies.

We assign the following headings to each of the paper's subsequent parts: The subsequent part provides a synopsis of the theoretical analysis and a study of the relevant literature. The third part is where the data and model specifications are laid out. The fourth section presents the econometrics technique. The fifth part contains both the findings and the commentary. The final part of this section presents the conclusion and the policy implications.

2. Literature review

Numerous researchers have been considering the causal interactions between energy consumption and economic growth and between energy consumption, CO_2 emissions, and economic growth in a variety of regions and timescales, using separate and dynamic panel studies, with varying degrees of success. We have merged the results of our empirical investigations. Table 1 summarizes the key findings from various studies that explore the correlation between energy consumption and economic growth, as well as the relationship between energy consumption, CO_2 emissions, and economic growth.

Table 1
Summary of previous studies.

Author	Period	Country/ Region	Key methodology	Key Causality/ Findings
Akadiri et al [5]	1700	Saudi Arabia	ARDL, Granger causality	NGC → GDP, GDP → TT
El-Karimi (2021)	1980–2019	UK and Germany	Granger causality	GDP ↔ REC, GDP→ NREC
Singh and Jasvinder [6]	1985–2019	India	ARDL	
Pinzón [7]	1970–2015	Ecuador	ARDL, Granger causality	
Ahmad et al. [8]	1995–2017	50 countries	ARDL, Cointegration	E → Y, E2Y
Andjarwati et al. [9]	1995–2017	Malaysia	ARDL, ADF	E → CO2 (+), Urb → CO2 (−), Y → CO2 (+)
Awodumi and Adewuyi [10]	1980–2015	5 African countries	ARDL	Gas E → Y(+), E → Y(−)
Dat et al. [11]	2000–2019	Indonesia	ARDL, ADF, Johansen	Y→E
Ghazouani et al. [12]	1980–2017	4 Asia Pacific	Bootsp ARDL	RE → Y, RE-TO (+)
Akorede and Afroz [13]	1970–2017	Nigeria	ARDL	Urb → E, E → Y, E→ CO2
Ferdaus et al. [14]	1990–2015	11 countries	ARDL, VECM	E → EP(−), E → Y, EP→Y
Ha and Ngoc [15]	1971–2017	Vietnam	Asymmetric, ARDL	E → Y, ELC → Y
Odugbesan and Rjoub [16]	1990–2014	4 MINT countries	ARDL	E → Y, Y→ E
Humbatova et al. (2020	1995–2017	Azerbaijan	ARDL, ADF, KPSS, PP	ELC2Y
Samuel et al. (2020)	2001–2018	Nigeria	ARDL, ECM,	Ser ≠ Y, Ind Energy ≠ Y
Sapnken et al. [17]	1994–2014	Cameroon	ARDL, VAR, Granger, TY	LPG2Y, Y → Ker, Urb→ Ker, Price →
Sapvan et al. (2020)	1990–2014	Yemen	ARDL	FD ≠ ER, Y → FDI(+), FD → FDI(−)
Selvanathan et al. [18]	1990–2014	South Asia	ARDL	T → Y, T → CO2, T → E
Shahani & Bansal (2020)	1970–2014	China India	ARDL, ECM	E → Y (−), E → CO2
Singh & Vashishtha [1]	1970–2015	India	ARDL, ECM, Granger	E ≠ Y
Smolovic et al. (2020)	2004–2018	EU, 28 countries	ARDL, PMG	RE →Y (New EU), RE ≠ Y (old EU)
Tamba (2020)	1975–2016	Cameroon	ARDL, ECM,TY, ADF, Johansen	LPG2 Y
.Zeraibi et al. [19]	1980–2018	China	NARDL	Y → E (−)
Uzokwe and Onyije [20]	1984–2015	Nigeria	ARDL, VAR	RE→ Y
Wang et al. [21]	1972–2017	Pakistan	ARDL, VECM	E → Y, Y → FD, Y
Adekoya (2021)	1990–2017	China	AMG, ARDL, DFE, PMG	O → Y(−)
Li et al. [22],b)	1995–2018	3 SAARC countries	PVECM	RE → Y
Bashir et al. [23]	1985–2017	Indonesia	EKC, VECM, Granger	E → Y
Belal et al. [24]	1990–2019	Saudi Arabia	VECM	Res E Y, Y/ = Ind E
Halkos and Gkampoura [25]	1990–2017	119 countries, EKC	E, NRE, RE, GDP, ELEC	
Kahia et al. (2021)	1990–2016	Saudi Arabia	EKC	RE → Y

(continued on next page)

Table 1 (*continued*)

Author	Period	Country/ Region	Key methodology	Key Causality/ Findings
Zhang and Zhang [26]	2000–2017	China-30 Provinces	VECM, Granger	CO2 2 Y, CO2 2 TOU Y2 Tou
Jayasinghe and Selvanathan [27]	1991–2018	India	ARDL, VECM	E → Y
Odhiambo [28]	1980–2016	Botswana,	ARDL Bounds testing,	E → Y
Krkoskova [29]	2005–2019	V4	Panel cointegration	E → Y(Czech, Hungary, Slovakia), E≠ Y (Poland)
Moftah and Dilek [30]	1985–2016	MENA	ARDL, TY (1995)	Y → E
Okoye et al. [31]	1981–2017	Nigeria	ARDL	E → Y
Thapa-Parajuli et al. [32]	1980–2018	Nepal	ARDL, Granger	E → Y(+),X → Y(+),Y → X, E → X

2 (−), (+) represent, +→, 2, and ≠represent unidirectional causality, bidirectional causality, and no causality, respectively.

2.1. Energy consumption and economic growth

Several notable studies have delved into the intricate relationship between energy consumption and economic growth, shedding light on their interconnectedness and the underlying mechanisms at play. These studies collectively contribute to our understanding of how energy consumption influences economic growth and underscore the importance of adopting strategies that balance economic objectives with environmental sustainability. Thapa-Parajuli et al. [32] examine the relationship between short- and long-term energy usage, competitiveness, and infrastructure prosperity in a northern developing economy. The evidence-based analysis confirms that trades have a relatively significant impact on income progress. Evidence suggests a unidirectional correlation between trade and GDP growth, energy usage and economic growth, and trade and energy consumption, as shown by the findings of the tests of causality. Okoye et al. [31] predict the impact of energy consumption on Nigeria's GDP from 1981 to 2017, taking into account gross fixed investment growth, inflation, and financial growth to ensure that their findings are as robust as possible. The analysis concluded that both the quantity of energy used and the amount of gross fixed capital created significantly influence economic growth in Nigeria. As a result, it concludes that energy consumption is a factor determining the expansion of Nigeria's economy, which follows the electricity hypothesis. Moftah and Dilek [30] investigate the temporal correlations between economic development and energy usage in sixteen countries chosen from North Africa and the Middle East. The limits test reveals that there is a consistent relationship between total final energy consumption and economic expansion over a long period of time. On the other hand, the causality test reveals that the flow of causation is one-way, from growth in the economy to total energy consumption; this finding suggests that energy conservation programs are unlikely to inhibit economic expansion. (2021) examines the long-term relationship between real GDP and energy usage for the V4 countries from 2005 to 2019. Granger's energy consumption has a long-term effect on GDP in Slovakia, Hungary, and the Czech Republic, suggesting that energy consumption may contribute to the expansion of these three countries' economies. This essay's conclusions reveal that none of the V4 nations confirm bidirectional causation, but the Czech Republic, Slovakia, and Hungary confirm the causal relationship between energy consumption and GDP growth. Odhiambo, N. [28],[33] evaluated energy use and economic growth in Botswana from 1980 to 2016. The study suggests that economic expansion greatly boosts energy usage. It demonstrates that energy use has not driven Botswana's economic growth. It also demonstrates that achieving energy savings does not impede economic growth. Belal et al. [24] analyze the correlation between Saudi Arabia's rising electricity use and GDP expansion. It seems that industrial power consumption's KSA is inelastic due to changes in energy costs compared to economic growth, as shown by the long-term serial correlation between the series, whereas residential electricity consumption displays an elastic connection. It would appear from the results of a Granger causality test that higher levels of industrial electricity consumption are directly attributable to the expansion of economic activity at higher levels. The authors, Li et al. [22],b), analyze the South Asian Organization for Regional Cooperation countries' economic growth concerning their use of renewable energy sources. The overall data demonstrates that all three forms of renewable energy significantly contribute to the expansion of the economies of the countries that make up SAARC. Adekyo (2021) investigates the correlation between energy usage (oil) and economic growth by taking into account the impact of China's natural resource endowments (1990–2017). Utilize the dynamic heterogeneous panel estimators of the Panel ARDL model to account for the data's heterogeneity and non-unit roots. According to the base model's conclusions, the long-term impact of oil consumption on the economic development of resource-rich nations is negative, while the short-term effect is positive. On the other hand, the use of oil does not have a substantial impact, either in the short run or the long run, on the expansion of the economy in resource-deficient nations. This essentially implies that a lack of available energy resources, through a variety of transmission mechanisms, is responsible for this result. Using data from Pakistan, Wang et al. [21] aim to explain the correlation between GDP growth and durability. The variables under consideration confirm cointegration. Additionally, there is a correlation between a rising standard of living and a longer life expectancy. The current state of Pakistan's life expectancy is negatively affecting the country's financial development. The degradation of ecosystems due to human energy consumption reduces human lifespan. Uzokwe and Onyije [20] employed an ARDL approach, a VAR, an estimated Granger causality test, and a Wald test to investigate the link between the use of renewable and non-renewable energy sources and the GDP growth in Nigeria from 1984 to 2015. This study covers the period from 1984 to 2015. It would seem that there is a strong positive correlation connecting non-renewable energy consumption (NREC), renewable energy consumption (REC), and GDP in both the short term and the long term; however, there is no evidence to suggest that there is a causal relationship between these three variables. According to the findings, both the NREC and the REC contribute significantly to the growth of the economy in Nigeria. Zeraibi et al. [19] explore the possible impacts of energy use and technological innovation on China's economic growth from 1980 to 2018. The use of the econometric approach known as Non-Linear Autoregressive Distributive Lag (NARDL) reveals that there is an unbalanced relationship between technological innovation, energy consumption, and economic progress in China. To uncover this finding. The research concluded that residential energy use accounted for a significant proportion of China's total energy consumption, despite widespread belief to the contrary. The empirical results also imply that the Chinese government should regulate suitable policies to encourage energy efficiency and restrict the use of energy in inefficient ways. Tamba [34] investigates the relationship between Cameroon's consumption of liquefied petroleum gas (LPG) and the country's overall GDP growth from 1975 to 2016. The study covers the period from 1975 to 2016. According to the ECM causal tests, there is a short-term direct link between LPG use and economic growth. There is also a bidirectionally significant correlation between long-term factors and increased variables, but the cointegration techniques show that the relationship is level. These findings suggest a correlation between increased LPG consumption and economic growth. Therefore, Cameroon is unable to endorse energy efficiency policies aimed at reducing the consumption of liquefied petroleum gas. From 2004 to 2018, Smolovic et al. [35] investigated the relationship between the use of renewable energy sources and economic development in both old and new EU member states. They employed a pooled mean group (PMG) estimator in a dynamic panel setting to closely examine the connections between some variables (an ARDL model). Renewable energy usage has a statistically significant long-term beneficial effect on economic development in both nations. Positive influence supports this conclusion. In new member states, renewable energy use has a negative short-term effect on economic activity, but no statistically significant influence in traditional member states. Between 1970 and 2015, Singh and Vashishtha [1] analyzed the correlations between India's energy use and its gross domestic product per capita. Singh and Vashishtha [1] employed three distinct methods to examine the significance of the data: Johnson cointegration, vector autoregression, and the Granger causality test. The results showed that there was a one-way causation from GDP per capita to energy consumption per capita, as well as no evidence of a link that maintained the above two independent variables in long-term equilibrium in India. Between 1980 and 2019, El-Karimi (2022) analyzed the correlations between the use of renewable and nonrenewable energy sources and GDP growth in the three European countries of Germany, the United Kingdom, and France. El-Karimi [36] conducted this analysis using both the Toda-Yamamoto-developed temporal causality test and the frequency Granger causality. The results support the neutrality hypothesis by demonstrating that GDP and RECdo not have a significant causal relationship in either the United Kingdom or France. The results for NREC are consistent with one another. Yet, the frequency method demonstrates a bidirectional relationship between REC and GDP, while the time approach demonstrates only a unidirectional causal link. Policymakers in the United Kingdom and France need to reflect on the fact that renewable energy and energy conservation regulations do not affect economic development. Sapnken et al. [17] identify and measure the short- and long-term consequences of kerosene and LPG consumption growth patterns in Cameroon from 1994 to 2014. Prices, income, and urbanization all have a positive influence on kerosene and LPG consumption in the short and long term, resulting in a significant shift from kerosene to LPG. The Granger causality tests indicate that there is a two-way relationship between LPG usage and income, but not with kerosene. The feedback loop between LPG usage and economic development is significant. As a result, Cameroon is in a position to support energy policies that aim to promote LPG usage while simultaneously reducing kerosene use. Humbatova et al. [37] examined the relationship between electric energy usage and GDP growth in Azerbaijan from 1995 to 2017. In a variety of economic subsectors, empirical studies reveal a positive link between GDP, electric energy consumption, and GDP. Ha and Ngoc [15] used asymmetric ARDL cointegration to examine how energy use affected Vietnam's economy from 1971 to 2017. The study's findings suggest that both the short- and long-term impacts of electricity consumption on economic development are asymmetric, with a greater impact from negative changes on growth than from positive ones. Long-term, favorable changes in petroleum consumption have a higher influence on economic growth than negative ones. The causality test confirmed the validation hypothesis by showing bi-directional causation between energy consumption and economic development. Stungwa et al. [38] investigated the correlation between electricity consumption and economic growth in South Africa from 1971 to 2014. The research findings, based on the ARDL model, showed that there is a statistically significant short-run relationship and a positive long-run relationship between renewable electricity consumption and South Africa's economic growth. Saidi et al. [39] explore the dynamics among energy consumption, information technology and communication (ICT), foreign direct investment (FDI), and economic growth across 13 MENA countries from 1990 to 2012 using dynamic panel data. They apply panel unit root and cointegration tests, along with Granger causality tests. The econometric analysis reveals a bidirectional relationship between energy consumption and economic growth (feedback hypothesis). Additionally, a bidirectional relationship exists between ICT and economic growth in both the short and long run. However, the results suggest a unidirectional causality from economic growth to FDI. The study underscores the significance of energy consumption and ICT in shaping economic growth. Samargandi et al. [40] [41].analyze the distinct effects of financial development on both the oil and non-oil sectors on economic growth, covering the period from 1968 to 2010, within the framework of Saudi Arabia, an economy abundant in oil resources. Using the autoregressive distributed lag (ARDL) bounds test technique, they observe that financial development has a positive influence on the growth of the non-oil sector. In contrast, its impact on the oil sector and overall GDP growth is either negative or statistically insignificant. Ozturk [42] [43].uses the bivariate vector autoregression model and the Granger causality approach introduced by Toda and Yamamoto [44] to look at the relationship between energy consumption and real GDP in 11 countries in the Middle East and North Africa from 1971 to 2011. Causality tests reveal: (1) unidirectional causality from energy consumption to real GDP in Egypt, Iran, Lebanon, and Tunisia; (2) unidirectional causality from real GDP to energy consumption in Algeria, Morocco, and Saudi Arabia; (3) bidirectional causality in Oman and the United Arab Emirates; and (4) no causality between energy consumption and real GDP in Bahrain and Malta. These findings suggest that energy conservation policies can be effective in Algeria, Bahrain, Malta, Morocco, and Saudi Arabia, offering valuable policy implications. Awodumi and Adewuyi [10] investigate the effects of non-renewable energy on economic development and carbon emissions in the major oil-producing countries in Africa from 1980 to 2015. Positive non-renewable energy use in Nigeria slows growth but decreases emissions. Egypt and Nigeria respond similarly to positive and negative petroleum and natural gas consumption. To stimulate economic expansion and ensure that oil-producing countries in Africa can keep consuming the vast quantities of petroleum and natural gas that they produce, officials will need to make investments in carbon-reducing technology and actively push its use in production processes. Andjarwati et al. [9] examine the connection between environmental degradation in Malaysia and variables such as energy consumption, economic development, urbanization, industrialization, and poverty levels using data from 1995 to 2017. The research findings indicate that energy consumption has both a positive short-term and a positive long-term effect on environmental quality. On the other hand, urbanization is one of the factors that contributes negatively to environmental deterioration over the long term, in contrast to population growth, industrialization, and poverty, all of which positively contribute to environmental degradation. Only in the short run does economic growth make a positive contribution to the degradation of the environment. The government should produce energy by utilizing renewable sources, which have a smaller impact on environmental degradation. Apergis and Payne [45] investigated the relationship between natural gas consumption (NGC) and GDP growth in 67 countries. They focused on the period from 1992 to 2005 and utilized the Vector Error Correction Model (VECM) technique. According to the findings, there is a bidirectional relationship between gas use and GDP growth. Using the ARDL model, Bildirici and Bakirtas [46] investigated the same variables in BRICS+2 countries from 1980 to 2011. The study found a bi-directional relationship between NGC and economic growth in Brazil, Turkey, and Russia. Furthermore, Aydin [47] conducted a significant study in which he investigated the top ten nations in terms of natural gas consumption. The purpose of this investigation was to determine the long-term and short-term link between NGC and economic growth (EG) from 1994 to 2015 using the panel Granger causality test. The empirical findings demonstrate that both NGC and GDP growth are positively and significantly impacted in the long run. Alternatively, the Granger causality test showed that the United Kingdom, Thailand, and Germany have a transitory relationship with EG and NGC. Dong et al. [48] used the Environmental Kuznets Curve (EKC) to analyze GDP and natural gas consumption in 14 Asian-Pacific nations (including Bangladesh) from 1970 to 2016. The findings showed that 13 of the 14 countries satisfy the EKC hypothesis. Furuoka [49] analyzed the correlation between natural gas consumption and economic growth in China and Japan from 1980 to 2012 using the ARDL approach. The empirical findings of the study revealed a significant relationship between natural gas consumption and economic growth in both countries. Using panel data spanning the years 1991–2015, Zhi-Guo et al. [50] examined the same variables across Northeast Asian nations, specifically China, Japan, and Korea. This study fails to uncover a causal relationship between NGC in either Japan or Korea, but it indicates a relationship in China. Fatai et al. [51] highlighted that there is no substantial relationship between energy consumption and economic growth in Asian countries such as India, Indonesia, the Philippines, Thailand, Australia, and New Zealand. Ghazouni et al. [12] investigate the relationship between openness to trade, use of renewable power, and economic development in seven Asian and Pacific nations from 1980 to 2017. With the exception of Malaysia, there is no correlation between real trade openness, real electricity consumption, and real GDP per capita. Indonesia, Japan, South Korea, and Thailand exhibit cointegration patterns that depend on trade openness. Renewable electricity consumption yields similar results for Indonesia, Malaysia, and Thailand. Short-term causality analysis shows mixed results for different countries. Outcomes influence trade, energy, and environmental policy. Consumption of renewable energy will rise as a direct result of any environmental policy that decreases emissions of carbon dioxide and non-renewable forms of energy. This may have a positive impact on economic development and openness to trade. From 1990 to 2013, Ferdaus et al. [14] used a multivariate panel framework to examine the effect of energy use and pricing on economic development for three groups of 11 nations. The panel autoregressive distributed lag estimate method reveals that energy consumption has a positive effect on long-term economic development and a negative effect on short-term economic growth across 11 countries. Panel causality studies confirm a unidirectional causal relationship between economic expansion and energy use. According to the Dynamic Ordinary Least Squares panel, high energy usage and prices have a negative impact on economic development. Energy consumption has a negative effect on economic growth, and energy prices have a positive effect, but both have a negative effect in the short run, according to results from a Panel Autoregressive Distributed Lag estimation.

2.2. Energy consumption, CO2 emissions, and economic growth

The link between energy consumption, CO2 emissions, and economic growth presents a nuanced perspective. Heightened economic growth and increased energy consumption often correlate with elevated CO2 emissions, driven by intensified industrial operations, expanded transportation infrastructure, and augmented energy production. Bashir et al. [23]. This phenomenon carries negative implications, contributing to environmental degradation, climate change, and associated health risks. Conversely, there are positive dimensions to consider. Increased energy consumption, while fueling economic expansion, can stimulate technological breakthroughs and innovations in clean energy solutions, potentially leading to lower emissions per unit of economic output. Moreover, strategic investments in renewable energy sources and energy efficiency initiatives have the dual benefit of stimulating economic development while concurrently mitigating CO2 emissions. This study utilized the theoretical underpinnings of the ARDL and VECM models. Jayasinghe and Selvanathan [27] examine the correlation between India's energy consumption, GDP, carbon dioxide emissions, and the number of foreign sightseers who visited the country between the years 1991 and 2018. Tourism and energy consumption are two major factors contributing to increases in CO2 emissions, according to the findings. They identify a unidirectional causal relationship between long-term CO2 emissions, GDP, energy consumption, GDP per capita, and the number of tourists visiting a country. Specifically, Bashir et al. [23] suggest that the consumption of energy and urbanization cause CO2 emissions in the short run and that urbanization can cause energy use. In this context, other findings indicate the existence of long-term connections between energy consumption, GDP, and CO2 emissions in the context of urbanization, as well as the reverse relationship. Energy consumption, carbon dioxide emissions, and India's GDP are all topics explored by Singh and Jasvinder [6]. They also consider the impact of other factors, such as FDI, urbanization, inflation, and farmlands. According to the investigation's results, there is a cointegration relationship between the variables. Short-term issues that have a major influence on economic growth include energy consumption, carbon dioxide emissions, inflation, and the supply of agricultural land. Yet, although inflation and the decrease in agricultural land have large negative effects on economic development, carbon emissions are a driver of good long-term effects. To investigate the connection between GDP growth, energy usage, and pollution hotspots, Zhang and Zhang [26] use a regional analytic model using panel data across 31 Chinese provinces between 2008 and 2018. The results indicate a spatial relationship between China's economic expansion, energy system, and CO2 emissions, with distinct areas where they cluster together. Using a simultaneous equation modeling strategy, Khia et al. (2021) investigated the connection between GDP growth, consumption of renewable energy, and environmental sustainability in Saudi Arabia from 1990 to 2016. The most important results are that (i) economic growth has a one-way, causal effect on renewable energy consumption, which supports the conservation hypothesis; (ii) economic growth, CO2 emissions, and renewable energy consumption are all related in two ways; and (iii) Saudi Arabia's renewable energy has not been able to balance environmental protection and economic growth. Halkos et al. [25] conducted a Granger causality analysis of the correlation between fossil fuel power production and renewable electricity generation in 119 countries across the world with varying per capita incomes. Countries with high and upper-middle incomes support the hypothesis, while those with low and low-middle incomes do not. Across all income levels, research reveals a bidirectional Granger causation between GDP per capita and CO2 per capita. According to Jayasinghe and Selvanathan [27], both tourism and energy use are factors that contribute positively to CO2 emissions. The study demonstrates a unidirectional causal relationship between energy consumption, gross domestic product per capita, and the number of tourists visiting a country with high carbon dioxide emissions. Based on the findings, it seems that India's economic development strategy should prioritize environmentally responsible tourist practices, increased energy consumption, and overall economic expansion. To ascertain the Granger causal link between energy consumption (EC) and economic growth (EG) in Ecuador, Pinzón, K. [7],[52] examines aggregated and disaggregated data from 1970 to 2015. He found that the following trends are evident in Ecuador: (1) energy consumption leads to environmental degradation without any impact; (2) energy consumption exhibits a bidirectional causal link with environmental degradation in the transportation sector; (3) the consumption of oil and hydroelectricity appears to be the source and impact of environmental degradation; and (4) the economic growth of Ecuador's economic sectors contributes to environmental deterioration in some way. Muhammad [53] examines the effect of economic growth, energy consumption, and CO2 emissions on each other for a panel of 68 countries. Selected panel data from 68 nations from 2001 to 2017 for developed, emerging, and MENA countries. Data analysis using GMM and Sys GMM. The calculated empirical results show that energy consumption increases economic growth in industrialized and rising countries but decreases in MENA countries, while CO2 emissions increase in all countries. Increased CO2 emissions boost energy consumption and economic growth in all nations except MENA. CO2 emissions increase while energy consumption decreases in rich and MENA nations, but emerging countries' energy consumption increases, and CO2 emissions fall due to economic expansion. Gorus and Aydin [54] explore the causal relationship between energy consumption, economic growth, and CO2 emissions in eight oil-rich MENA countries (Algeria, Egypt, Iran, Iraq, Oman, Saudi Arabia, Tunisia, and the United Arab Emirates) from 1975 to 2014. Both single- and multi-country Granger causality analyses in the frequency domain were conducted. The panel frequency domain analysis reveals more causal connections between variables at different frequencies compared to time domain causality. Results from panel causality tests indicate that energy conservation policies don't adversely affect economic growth in the short and intermediate run but exhibit negative effects in the long run. Shahani and Bansal [55] examine the co-integrating link between economic development, energy, and the environment between 1970 and 2014 for both India and China. We use carbon dioxide emissions per capita as a proxy for environmental degradation, fossil fuel consumption as a proxy for total energy consumption, and gross domestic product per capita as a proxy for growth. The study's results suggested a correlation between all the variables, except CO2 (China), which we selected as the dependent variable. The phrase "error correction model" always had a negative and significant effect, no matter what the situation was. Selvanathan et al. [18] examine the connections between tourism, energy use, CO2 emissions, and GDP in South Asia using data from 1990 to 2014. They achieve this by employing autoregressive distributed lags, vector error correction models, and panel models. They conclude that, in the long run, tourism makes a significant contribution to GDP, CO2 emissions, and energy consumption; an increase in GDP enhances tourism, and an increase in CO2 levels does not dissuade visitors from approaching South Asia. From 1993 to 2017, Odugbesan and Rjoub [16] examined the link between economic growth, CO2 emissions, urbanization, and energy consumption in MINT (Mexico, Indonesia, Nigeria, and Turkey) nations. The energy-growth hypothesis, which believed that energy consumption had a unidirectional causal link with economic development, was accurate for Nigeria and Indonesia, according to the results. The hypothesis assumed that energy consumption had a unidirectional causal relationship with economic growth. Mexico and Turkey followed the feedback theory, indicating a bidirectional link. All MINT nations link urbanization to economic development, energy consumption, and CO2 emissions. The report recommends energy-saving policies for MINT nations to boost economic development. Akorede and Afroz [13] [56]. analyze the long-term relationship and causality of energy consumption, economic growth, and CO2 emissions. The second step involves determining the long-term relationship and causality between the variables. The Granger causality test showed a bidirectional causality between urbanization and energy usage. The findings indicate that Nigeria's high energy consumption and slow economic development influence the country's short-term carbon dioxide emissions. Urbanization is a substantial factor, although it has a negative statistical impact, while energy consumption and economic growth both have a positive impact and are statistically significant. Hence, the research recommends taking action to lessen the impact on the ecosystem and stop any additional damage. Ahmad et al. [8] examine how renewable energy and pollution have affected economic development in Sub-Saharan African nations. However, the data from the study showed that renewable energy consumption and the reduction of pollution had a notable effect on economic expansion. Therefore, the examined studies propose a growth model that can assist African countries in better understanding and reducing their use of renewable energy and CO2 emissions in areas under their control, thereby ensuring long-term economic growth.

The literature reviewed reveals a lack of consensus among researchers regarding the relationship between energy consumption, CO2 emissions, and economic growth. This discrepancy arises due to variations in econometric models, time frames, country contexts, omitted variable bias, data availability, and variable selection. Thus, further research employing appropriate techniques and data is necessary to provide accurate information for policymakers. Additionally, our review of existing literature uncovered a gap regarding the influence of energy consumption and CO2 emissions on economic growth in developing countries. Consequently, our study addresses this gap by examining the short-run and long-run relationship between liquefied petroleum gas consumption (LPGC), natural gas consumption (NGC), other refined product consumption (ORPC), carbon dioxide emissions (CO2), and gross domestic product (GDP) in Saudi Arabia.

3. Data sources, specification model

3.1. Data sources

This study intends to investigate the link between economic growth, liquified petroleum gas consumption, natural gas per capita consumption, other refined product consumption, liquified petroleum gas per capita consumption, and carbon dioxide emissions in Saudi Arabia, taking into consideration the potential roles of economic growth and energy consumption. SAMA (Saudi Central Bank, 2022), the Ministry of Economics, and our World Data are the sources of data for every variable that makes up the nexus of this study. For empirical observations and analysis, the Saudi Arabia data cover the period from 1970 to 2021. Table 2 provides a comprehensive explanation of the variables, including their measurements and data sources. The data used includes consumption of liquefied petroleum gas (LPGC), natural gas consumption (NGC), other refined product consumption (ORPC), liquified petroleum gas per capita consumption (LPGPC), and carbon dioxide emissions (CO2). This data covers the period from 1970 up until 2021. The growth of the gross domestic product (GDP) was selected as the dependent variable (real GDP at constant 2015 dollars). We use this metric to quantify the expansion of the economy. We measure the level of environmental damage in thousand-ton increments of CO2 emissions resulting from the combustion of fossil fuels. We also express energy consumption variables like LPG and other refined products in thousand barrels per day (thousand B/D). Megawatt-hours (MWh) per person per year measure natural gas per capita consumption, while LPG per capita consumption serves as an indicator of liquified petroleum gas consumption per capita (aggregate LPGC/population) energy use. The author's contribution provides the information for constructing the LPG per capita indicators.

3.2. Statistical proprieties of the variables

In Table 3, we exhibit the descriptive statistics of the selected variables, which include the mean, standard deviation, minimum, maximum, skewness, and kurtosis, as well as the Jarque-Bera statistic for normalcy. Descriptive statistics are utilized to determine the chronological properties of data. However, the estimated results show that Log LPGC, Log NGC, Log ORPC, and Log CO2 are skewed negatively, while Log GDP is positively skewed. The result reveals that kurtosis has a positive value for all variables. According to the Jarque-Bera (reference) estimated values, all variables in the KSA economy are normally distributed.

Table 4 displays the pairwise correlation analysis, which

Table 2
Variables and definitions.

Variables	Description	Measuring Units	Sources
GDP	Gross domestic product	Real GDP Per Capita Constant 2015 USD	SAMA/Ministry of Energy
LPGC	Liquefied Petroleum Gas Consumption	Total of public and industry oil consumption Thousand B/D	SAMA/Ministry of Energy
NGPC	Natural Gas per capita Consumption	Megawatt-hours (MWh) per person per year	Our World in Data
ORPC	Other refined Products Consumption	Total of public and industry oil consumption Thousand B/D	SAMA/Ministry of Energy
LPGPC	LPG Per capita consumption	Per capita (Aggregate LPGC/Population)	Author's Contribution
CO2	Carbon dioxide emissions	CO2 emissions per capita in metric tons (1000 kg)	Our World in Data

Source: https://www.sama.gov.sa/en-us/economicreports/pages/database.aspx, https://ourworldindata.org

Table 3
Descriptive statistics.

	lnGDP	lnLPGC	lnNGC	lnORPC	lnCO2
Mean	9.9532	2.2373	12.0120	12.5509	2.6830
Median	9.8557	2.4465	12.3881	12.8015	2.6620
Maximum	10.5385	2.6687	13.4848	13.7565	3.0315
Minimum	9.6244	0.6283	9.0896	9.6881	2.0029
Std.Dev.	0.2631	0.5246	1.3072	1.1049	0.2139
Skewness	1.1776	−1.6935	−0.8568	−1.2643	−0.7740
Kurtosis	3.0306	4.8295	2.6447	3.7041	3.5675
Jarque-Bera	12.0217	32.1099	6.6368	14.9285	5.8910
Probability	0.00245	0.0000	0.0362	0.0005	0.0525

Data/country: KSA/1970–2021

Table 4
Correlation matrix.

	lnGDP	lnLPGC	lnNGC	lnORPC	lnCO2
lnGDP	1				
lnLPGC	−0.6534	1			
lnNGC	−0.6733	0.9814	1		
lnORPC	−0.6484	0.9258	0.9797	1	
lnCO2	−0.1743	0.6108	0.6987	0.7240	1

Data/country: KSA/1970–2021

demonstrates a negative relationship between GDP and LPGC, NGC, ORPC, and CO2. The estimated results reveal that LPGC, NGC, ORPC, and CO2 are positively associated with GDP.

3.3. Model specification

Considering the relevance of the consumption of energy in the economic process and real GDP in measuring economic growth, we analyze the potential effects of energy use on real GDP by specifying a production equation in the neoclassical economic growth framework that includes liquified petroleum gas consumption (*LPGC*), natural gas consumption (*NGC*), other refined product consumption (*ORPC*), liquified petroleum gases consumption per capita (*LPGPC*) and the usual carbon dioxide emission inputs (CO_2):

Our study establishes a theoretical framework to explore the dynamic interplay of *GDP*, *LPGC*, *NGC*, *ORPC*, *LPGPC*, and CO_2 in Saudi Arabia by referencing the methodologies of Karaaslan and Camkaya [57], Khan et al. [58], Wang et al. [59], and Alola et al. [60]. The model is organized as follows:

$$GDP_t = f(LPGPC_t, NGC_t, ORPC_t, CO_{2t}) \tag{1}$$

GDP appears to be a function of factors such as liquified petroleum gas consumption (*LPGC*), natural gas consumption (*NGC*), other refined product consumption (*ORPC*), LPG per capita consumption (*LPGPC*), and carbon dioxide emission (CO_2) in Equation (1).

Taking the ordinary square root of the variables to avoid multicollinearity, the ensuing rearrangement of the original expression (Equation (1)) was as follows:

$$ln\,GDP_t = \alpha + \beta_1\, lnLPGC_t + \beta_2\, lnNGC_t + \beta_3\, lnORPC_t + \beta_4\, lnCO_{2t} + \varepsilon_t \tag{2}$$

α is the intercept, β_1 and β_{21} are the explanatory variable coefficients. Where *ln* denotes the log transformation of both independent and dependent variables, and the period from 1970 to 2021 is denoted as *t*, and ε_t denotes the unbiased and equally distributed error term $(iid) \sim N\,(\mu\, r^2)$. Inside the context of the equation, β_1 stands for the LPGC coefficient, and it is anticipated that a positive sign will accompany this coefficient. β_2 is the NGC coefficient, and it should be positive or negative. β_3 is the ORPC coefficient, β_4 is the CO_2 coefficient, we predict that the coefficients of these values will either be positive or negative.

4. Econometric methodology

We have chosen the ARDL cointegration approach and the Toda-Yamamoto Granger causality test for several reasons. Firstly, the ARDL (Autoregressive Distributed Lag) model is highly flexible and suitable for small sample sizes, which is often a limitation in economic studies. It can handle variables regardless of whether they are stationary at level (I(0)), first difference (I(1)), or a combination of both. This flexibility eliminates the need for pre-testing the order of integration of variables, thus simplifying the modeling process and avoiding potential misspecification errors. Moreover, ARDL allows for the estimation of both short-term and long-term dynamics in a single reduced form equation, providing a comprehensive understanding of the relationship between oil consumption and economic growth over different time horizons. Secondly, we adopted the Toda-Yamamoto (TY) Granger causality test to explore the direction of causality between the variables. The TY procedure is advantageous because it does not require pretesting for unit roots and cointegration, which can be prone to errors and inconsistencies. Instead, it augments the VAR (Vector Autoregression) model by the maximum order of integration (dmax) of the series, ensuring that the asymptotic distribution of the test statistic remains valid. This robustness makes it a reliable tool for identifying causality, even in the presence of integrated and cointegrated processes. By combining these two methods, our study leverages the strengths of each approach to provide a rigorous and thorough analysis. The ARDL model helps establish whether a long-term equilibrium relationship exists, while the TY Granger causality test determines the causal direction without the complications of unit root and cointegration testing. This integrated methodology is particularly well-suited to the context of Saudi Arabia's economy, where the interplay between oil consumption and economic growth is complex and critical for policy implications.

4.1. Diagnostic tests of the model

If any of the series integrates into order 2, I(2), we cannot use the crucial constraints suggested by Pesaran et al. [61]. The ARDL methodology can only be utilized in situations involving sequences that are either I(0) or I (1), or both. In light of this, it is crucial to carry out a test for unit roots before moving on to the stage of estimation, to make sure that the cointegration methodology's ARDL limits approach holds under all possible circumstances. In this investigation, the existence of unit roots was investigated through the application of the augmented Dickey-Fuller (ADF) and the Phillips-Perron (PP) test procedures. To evaluate the sensitivity of the results, one effective strategy is to compare them using a variety of testing procedures. The PP test gives the results more credibility by omitting any consideration of a possible serial correlation in the series. As a result, time series data can be made more consistent, and autocorrelation can be corrected for heteroscedasticity. As a result, the employment of both the PP and ADF tests guarantees the establishment of a reliable model for examining the sequence in which the data presented in this paper were integrated.

4.2. ARDL bounds cointegration test

To examine the long-term link between the variables that were explored, this study applied the autoregressive distributed lag (ARDL) "Bound Test" approach that was initially given by Pesaran and Shin (1999) and Pesaran et al. [61]. To get rid of residual serial correlation and deal with the issue of endogenous variables (Pesaran and Shin, 1999), it is enough to make the necessary changes based on the ARDL model's instructions.

In this study, a multivariate method is used to explore the connection between GDP, LPGC, NGC, ORPC, and CO2 (see Fig. 1). To study the short- and long-term impacts of energy use on economic development, variables that cover extensive periods are required. The ARDL bounds test is utilized to assess the presence or absence of cointegration, after

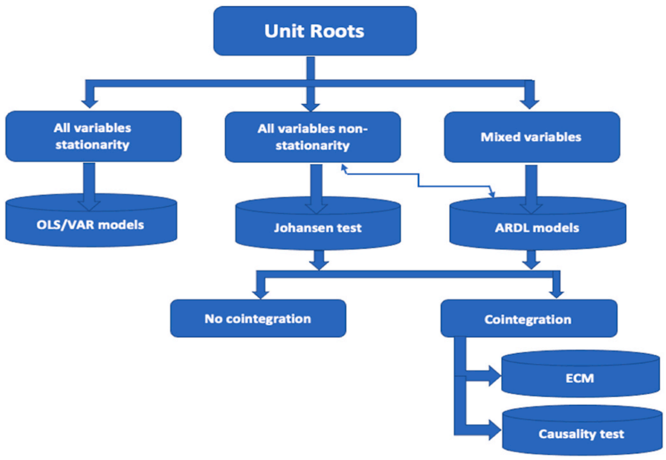

Fig. 1. Methodological framework.

which long-term and short-term dynamics are generated. Pesaran and Shin (1999) initially created and developed the ARDL bounds test method, and Pesaran et al. [61] further refined it, making it an appropriate methodology for identifying cointegration among variables. This strategy has a wide range of advantages in contrast to other cointegration methods. The ARDL bounds test's flexibility in handling data comes from its support for I(0) and I(1) variables, as well as a variety of delays. The ARDL method's single equation approach simplifies application and interpretation, but it does not guarantee that each series will have the same lag orders. It provides the most precise and reliable linear and independent estimation of the deep connection and long-run traits, eliminates endogeneity and autocorrelation issues in the series, and allows for the simultaneous assessment of the short-run and long-run correlations. Furthermore, it allows for dependable outcomes by mending the series' structural breaks and removing outlying data points. It is only through this approach that it will allow researchers to create long-term models that can explain the energy-growth relationship on a worldwide scale. ARDL models also help distinguish long-term linkages from short-term dynamics, which is interesting for examining economic issues. The following is an example of the generic form of the ARDL(p,q) model that may be written:

$$\Delta ln\ GDP_t = \alpha_0 + \sum_{i=1}^{p} \alpha_1 \Delta lnGDP_{t-i} + \sum_{i=0}^{q} \alpha_2 \Delta lnLPGC_{t-i} + \sum_{i=0}^{R} \alpha_3 \Delta lnNGC_{t-i} + \sum_{i=0}^{R} \alpha_4 \Delta lnORPC_{t-i} + \sum_{i=0}^{R} \alpha_5 \Delta lnOCO2_{t-i} + \beta_1\ lnGDP_{t-1} + \beta_2 lnLPGC_{t-1} + \beta_3 lnLPGC_{t-1} + \beta_4 lnNGC_{t-1} + \beta_5 lnOCO2_{t-i} + \varepsilon_t \tag{3}$$

GDP_t will serve as the dependent variable in this *investigation, while* LPGC, NGC, ORPC, and CO2 are variables of the study and $\varepsilon_t \sim iid\ (0, \sigma)$ *will represent the error term,* the distribution is homoscedastic and follows a regular pattern, ε_{t1}. The model that is depicted by Equation (3) is an illustration of a particular sort of error correction model (ECM), whereby the coefficients are not limited in any manner, shape, or form. This behavior is regarded as a "predisposed ECM," as stated by Pesaran et al. [61]. In light of the previously described equation, the following are the null and alternative hypotheses to consider:

H0. No cointegration exists.

H1. Cointegration exists.

To establish whether or not the variables have a long-term connection, an F-test is utilized:

$H_0 : \theta_0 = \theta_1 = \theta_2 = 0$

$H_0 : \theta_0 \neq \theta_1 \neq \theta_2 \neq 0$

As the test statistic distribution is fully unusual, no specific F-test critical values are accessible for any pairing of I(0) and I(1) variables; in addition, there is no such value that can be obtained. Using their findings, Pesaran et al. [61] conducted research to determine critical value boundaries for the asymptotic F-statistic distribution. They offer both lower and upper boundaries on crucial values for a variety of situations, such as those involving different variables (k + 1), among other things. Despite this, as the study is based on a rather small sample size, we will also compare the generated F-test value with the bounds in the statistical significance tables supplied by Narayan (2005). We can better understand the study's findings by using these tables, which are more suitable for use with smaller samples.

Both the lower and higher critical values determined by Pesaran et al. [61] are used to assess the F-statistic. In both cases, we assume that all of the variables are I(0) to establish the lower limit, and we assume that all of the variables are (1) to determine the upper bound. We regard the variables as I(0), meaning that cointegration cannot occur under any circumstances if the F-statistic is less than the theoretical limit. If the F-statistic is higher than the upper bound, then we can conclude that there is cointegration in the system. Lastly, if the F-statistic falls anywhere in the middle of the boundaries, the test is inconclusive, and an alternative approach to analyzing cointegration will be required. If the t-statistic for $ln\ GDP_{t-1}$ is greater than the I(1) bound, Eq. (2) supports a long-term link between the variables. If the t-statistic is less than the I(0) bound, then the data is invariant, indicating stationarity.

To estimate the short-run parameters, the regular error correction mechanism (ECM) is applied, as demonstrated by the equation below:

$$\Delta ln\ GDP_t = \alpha_0 + \sum_{i=1}^{p} \alpha_1 \Delta lnGDP_{t-i} + \sum_{i=0}^{q} \alpha_2 \Delta lnLPGC_{t-i} + \sum_{i=0}^{R} \alpha_3 \Delta lnNGC_{t-i} + \sum_{i=0}^{R} \alpha_4 \Delta lnORPC_{t-i} + \sum_{i=0}^{R} \alpha_5 \Delta lnOCO2_{t-i} + \tau ECT_{t-1} + \varepsilon_t \tag{4}$$

Error correction model results reveal how quickly a system will adjust to a short-term shock and reestablish its long-term equilibrium. The ECM considers both the short-run and long-run coefficients while preserving the long-run information. In the ECM approach, the negative and statistically significant value of the ECT coefficient represents long-run causation, whereas the significant value of the coefficients of other explanatory factors represents short-run causality. Long-run causality is represented by the ECM approach. We used the ECM approach to carry out this investigation (Rahman and Mamun, 2016; Shahbaz et al., 2013).

4.3. Diagnostic and stability models tests

The ARDL Bounds Testing methodology rests on a number of important and necessary assumptions, one of the most important and crucial of which is that the errors in Eq. (3) must be independent of each other and spread out in a normal way. In order to check for serial independence, we will use both the Q-Statistics and Breusch-Godfrey Serial Correlation LM tests. Furthermore, the "Jarque-Bera" test will be utilized in order to test for the Normality of the errors produced by the model. We will examine heteroscedasticity using the Breusch-Pagan-Godfrey test. Any model that contains an autoregressive structure must always have its "dynamic stability" checked and validated. When employing cointegration methods, it is critical to validate the model, as model misspecification can result in instability [62]. Following the advice of Pesaran and Pesaran (1997), we use the CUSUM of squares (CUSUMSQ) and the CUSUM of recursive residuals (CUSUM) to account for omitted variable bias and test for parameter instability.

4.4. Toda-Yamamoto (1995) Granger causality method

The presence of cointegration between time series may infer a Granger causality that is either unidirectional or bidirectional. The inverse, however, is not correct (Giles, 2011). Then, according to Granger (1969), we can't depend entirely on correlation measurements when trying to understand the connection between multiple time series. This is because certain associations may be erroneous and insignificant, suggesting the existence of uncontrollable independent factors. Even more so, cointegration alone doesn't prove cause and effect between variables. In other words, if we find cointegration in our series, we need to double-check our causality findings.

We can use the following vector autoregressive (VAR) model to determine whether Granger causality is present:

$$Y_t = g_0 + a_1 Y_{t-1} + \ldots + a_p Y_{t-p} + b_1 X_{t-1} + \ldots b_p X_{t-p} + \mu_t \tag{5}$$

$$X_t = h_0 + c_1 X_{t-1} \ldots\ldots + c_p X_{t-p} + d_1 Y_{t-1+\ldots\ldots} + d_p Y_{t-p} + \nu_t \tag{6}$$

Furthermore, we test H_0: $b_1 = b_2 = \ldots .. = b_p = 0$, against H_A: X causes Y. Similarly, we are testing the null hypothesis H_0: $d_1 = d_2 = \ldots .. = d_p = 0$, against the null hypothesis H_A: Y causes X. Each case where the null hypothesis is rejected provides evidence for the existence of Granger causation. Note that the "level" format provides both the X and Y series. This suggests that the data are not provided in "difference" form, in which μ_t and ν_t, are error terms that represent white noise. These errors ought to cancel each other out over the long term, bringing the equilibrium value back down to zero. Cointegration occurs in these two equations when at least one of the coefficients b_i or d_i which is statistically different from zero. The Yt and Xt series are considered cointegrated, in greater than zero and less than zero, hence, Yt and Xt are coupled in a vicious circle. There is no cointegration between Yt and Xt, however, if both b_i and d_i equal zero. If the sample size is too small, the cointegration and causality tests may produce inconsistent findings (with the preceding result of ARDL). This is possible if there are not enough people in the sample (Giles, 2011). The short-term dynamics between Yt and Xt are modeled by the coefficients b_i and d_i.

Following the methodology outlined in Toda and Yamamoto [44], Granger uses a method called augmented vector autoregression (VAR) to test for a causal connection between the variables. Using the standard procedures, we will determine the optimal maximum time interval between observations for each variable included in the VAR. We also use the AIC and other common data criteria to determine the lag time. Additionally, we will accurately describe the VAR and guarantee the absence of serial correlation in its residuals.

5. Results and discussion

5.1. Unit root test

Our investigation begins with a check to see if the series are stationary, followed by the establishment of the system's optimal lag length, k. In order to determine the order of integration, I_d, this study makes use of a total of two distinct unit root tests. The stationarity test of Phillips and Perron (PP) [63] and the augmented Dickey and Fuller (ADF) [64] are two examples of unit root tests. This is due to the debates that surround stationarity tests, hence, it may be possible to determine whether or not the data strongly supports stationarity or non-stationarity by comparing the results of many alternative tests. According to what was covered in Section 4.4.1, the first steps of the empirical investigation consisted of determining if the series is stationary and finding the optimum lag length, k, for the system. Table 5 shows the results of various additional unit root tests, including the ADF and PP tests. Even though some of the results are fractionally paradoxical, we cannot refute the non-stationarity null hypothesis H_0 regarding the time series lnGDP, lnLPGC, lnNGC, lnORPC, and lnCO2. We divide these series into two different orders, I(0) and I(1), as we correct the initial level and the first difference.

5.2. ARDL-bounds cointegration test

We can be sure of the strength of the cointegration relationship between LPG consumption, NGC, economic growth, and other variables such as ORPC and CO2 emissions using the ARDL bounds test method. This technique ensures accurate estimates, especially when dealing with relatively small sample sizes, surpassing the capabilities of conventional cointegration tests. A notable feature is its ability to simultaneously capture both long- and short-term dynamics within the fitted regression, incorporating the error correction model term (ECT). Moreover, this method proves invaluable when dealing with an unknown order of stationarity, whether it is I(0) or I(1), but not I(2). It operates within the framework of unrestricted error correction, assuming all variables are endogenous, showcasing its versatility and effectiveness in various analytical contexts.

This study uses the ARDL limits test to investigate the long-run link between LPGC, NGC, ORPC, CO2, and GDP. Two different information criteria—the Akaike Information Criterion (AIC) and the Schwarz Information Criterion (SIC)—are used to determine the lags in an equation to find the best possible solution (3). Table 6 presents the results of

Table 6
Lag length selection criteria for cointegration.

Lag	LogL	LR	FPE	AIC	SIC	HQ
0	13.018	NA	4.93e-07	−0.334	−0.139	−0.260
1	300.698	503.440	8.75e-12	−11.279	−10.109	−10.837[a]
2	329.474	44.362[a]	7.74e-12[a]	−11.436[a]	−9.292	−10.626
3	369.744	25.003	1.10e-11	−11.176	−8.057	−9.997

[a] Indicates lag order selected by criterion. **LR:** Likelihood ratio criterion. **FPE:** Final Prediction Error. **AIC:** Akaike information criterion. **SC:** Schwarz information criterion. **HQ:** Hannan-Quinn information criterion.

Table 5
Unit root tests analysis.

Variables	ADF test		PP test		Order of Integration
	Level	First Difference	Level	First Difference	
lnGDP	−2.3142	−5.2670*	−1.6421	−5.2352*	I(1)
	(0.1717)	(0.0001)	(0.4541)	(0.0001)	
lnLPGC	−2.4997	−8.2114**	−2.6310	−8.1609*	I(1)
	(0.1215)	(0.0000)	(0.0935)	(0.0000)	
lnNGC	2.3128	−6.3762*	2.3764	−6.4085*	I(1)
	(0.9999)	(0.0000)	(1.0000)	(0.0000)	
lnORPC	−5.2711		−4.3846		I(0)
	(0.0001)	(.)	(0.0009)	(.)	
lnCO2	−3.4228		−7.1505		I(0)
	(0.0146)	(.)	(0.0000)	(.)	

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

applying the two previously described criteria, indicating that two is the optimal number of lags. After determining the number of optimum lags, we will use the ARDL cointegration method for equation (3) to determine whether or not a link exists over the long term between the variables, which are the main focus of our research. After establishing the long-term relationships, the next step is to estimate the cointegration link between the variables (see Table 9).

Table 7 presents the results of cointegration test from Pesaran et al. [61], indicating a rejection of the no-cointegration hypothesis at a minimum threshold of 10 % for all variables. This suggests a long-term association among LPGC, NGC, ORPC, CO2, and GDP from 1970 to 2021, with these five variables following a shared trend. Furthermore, to further validate the robustness of F-statistics, we incorporate Johansen cointegration, as detailed in Table 8. The Johansen cointegration analysis, as reported by Johansen [65], yields both trace statistics and eigenvalues. In particular, both statistics indicate the presence of at least three cointegration relationships, which leads to the rejection of the null hypothesis of no cointegration. These findings underscore the robust nature of the long-term equilibrium relationships identified among the integrated variables, regardless of the normalization applied.

We conclude that the model is legitimate and correctly specified, as demonstrated in all evaluations. Therefore, we carry out the bound test as the second step in the process. Table 7 presents the results of the ARDL bounds test and demonstrates that the Fisher statistic value is greater than the upper bound for the various significance levels for each specification. As a result, we reject the null hypothesis H_0, which claims that there is no long-term association between the different variables. Instead, we conclude that there is a long-term association between variables.

As a consequence of this, the results of the cointegration tests that were carried out using [61] as a reference can be found listed in Table 7. If each variable meets the 10 % threshold requirement, the findings invalidate the no-cointegration hypothesis. We express this within the context of the ongoing conversation. For this reason, we deduce that LPGC, NGC, ORPC, CO2, and GDP all have a long-run correlation. Furthermore, we recommend the Johansen cointegration in Table 8 of this study to confirm the validity of the F-statistics. Regardless of the normalization used, this last one indicates the total number of long-term equilibrium connections among integrated variables of the same order. The output of the Johansen cointegration [65] generates two types of statistics: trace statistics and eigenvalues. It is plausible to reject the null hypothesis that there is no cointegration based on the results of these two statistical tests, which indicate that at least three cointegration connections exist at present.

Table 7
Cointegration tests [61].

Estimated model	Bound testing to cointegration		
	Optimal lag length	F-statistic	Cointegration
F_{GDP}/[GDP/LPGC, NGC, ORPC, CO2]	2,1,0,2,1	9.5466*	Yes
F_{LPGC} /[LPGC/GDP, NGC, ORPC, CO2]	2,0,0,1,0	4.8179*	Yes
F_{NGC}/[NGC/GDP, LPGC, ORPC, CO2]	1,2,2,2,0	11.5436*	Yes
F_{ORPC}/[ORPC/GDP, LPGC, NGC, CO2]	1,2,0,0,0	23.6516*	Yes
F_{CO2}/[CO2/GDP, LPGC, NGC, ORPC]	2,1,2,0,0	5.3318*	Yes
Significance level	Lower bound I (0)	**Upper bound I(1)**	
10 %	2.2	3.09	
5 %	2.56	3.49	
1 %	3.29	4.37	

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

Table 8
Johansen Cointegration test.

Hypothesized No. of CE(s)	Eigenvalue	Trace statistic	5 % critical value	Prob.
None*	0.7186	128.8189	69.8188	0.0000*
At most 1*	0.5071	65.4054	47.8561	0.0005*
At most 2*	0.3084	30.0312	29.7970	0.0470**
At most 3	0.1916	11.5290	15.4947	0.1776
At most 4	0.0189	0.9550	3.8414	0.3284

Note: *, and ** indicate significance at 1 %, and 5 % levels, respectively.

5.2.1. *Long-run relationships*

We use the ARDL estimation method, developed by Pearson et al. (2001), to estimate the coefficients of correlation in both the short and long run. Table 9 presents the empirical results, which show that the GDP growth rate reacts to changes in the present and delayed values of the independent variable, including the lagged values of the economic growth rate itself. The findings reveal a robust first-order autoregressive (lag) effect of economic growth, which insinuates that the current growth rate of GDP is deduced by its first preceding periods. The negative value recommends that GDP during the period firmly retards the display of economic performance. This agrees with the results of Okoye et al. [31], Moftah and Dilek [30],[66] Jayasinghe and Selvanathan [27], and Khia et al. (2021), which show a negative effect of lagging GDP on the current rate of economic performance. Both the current and first-lag values of liquified petroleum gas usage have a considerable effect on GDP. The robustly detrimental impact of lagged LPGC suggests that the value of economic activity in the period immediately preceding the current, measured by the consumption of liquified petroleum gas, inhibits the economy's capacity to grow in the current period. The growth retarding impact of lagged LPGC contrasts with the positive effect, resulting in Sapnken et al. [17]. Tamba (2020), Awodumi and Adewuyi [10], Jayasinghe and Selvanathan [27], and Thapa-Parajuli et al. [32] have suggested that the use of energy positively contributes to the expansion of the economy. It demonstrates very clearly that current natural gas consumption has a strong positive effect on overall economic growth. The result implies that the first-period lagged value of the NGC leads to improved performance. According to Akadiri et al. [5] and Awodumi and Adewuyi [10], natural gas consumption has a favorable influence on the expansion of the economy. Furthermore, the study shows a close relationship between economic growth and both the current and historical levels of other refined product consumption (ORPC). The results signify that, at a 10 % level of significance, an increase in the current value of ORPC (other refined product consumption) by 4.080 % stimulates GDP, while an increase in the value of ORPC in the past has had variable effects on growth. Therefore, the first period's lagged value of ORPC slows down the current growth performance of Saudi Arabia's economy. We show that the final variable in the model, representing CO2 emissions, has a single lag value. Furthermore, CO2's estimated short-run elasticity concerning GDP per capita is positive and statistically significant. This indicates that the relationship between the two variables is substantial. We find that a 1 % increase in CO2 levels stimulates economic growth by 3.6171 %. However, this coefficient is negligible, indicating that CO2 does not have a long-term effect on GDP in the KSA. (Dugan and Turkekul, [67] [68], Safi et al. (2021), Nathaniel & Sadeleyi (2021), Li et al. [22],b). In contrast to Piatowska and Geise (2021) and Halkos and Gkampoura [25]. Model diagnostics reveal that the R-squared value is 0.974, which indicates that 97.4 % of the variation in growth is explained by the regressors. Also, the F-statistic (10.5062) provides evidence that the regressors contribute significantly to the overall explanation of economic growth. The Durbin-Watson (D-W) score of 1.8916 indicates that the data does not have a serial connection. In particular, the model reveals remarkable potential to support a variety of different policy approaches.

Table 9
Estimated coefficients from the ARDL model.

Dependent variable: lnGDP					
Short-run results			Long-run results		
	Coefficients	t-Values	Regressors	Coefficients	t- Values
Δ lnGDP	−0.2213	−2.3863**	lnGDP	−0.2213	1.9819*
Δ lnLPGC	0.1833	2.1998**	lnLPGC	−0.3540	−3.1535*
Δ lnNGC	0.3974	4.0310*	lnNGC	0.6233	3.9951*
Δ lnORPC	−0.0083	−0.1055*	lnORPC	−0.6761	−3.3968*
Δ lnCO2	0.2321	3.6171*	lnCO2	0.2002	1.1484***
CointEq(-1)	−0.3820	−8.4590*	Constant	4.2062	−6.3950*
Diagnostic test statistics					
LM Test:	0.7152				
Jarque-Bera test	1.7203				
F-statistic	10.5062				
ARCH test	0.5880				
DW-statistic	1.8916				
Hetsroscedasticity test	0.8245				
R-squared	0.9747				
Stability Analysis					
CUSUM	Stable				
CUSUMQ	Stable				

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

5.2.2. *Error correction model results*

According to the estimates presented for the short run in Table 9, each factor has a major influence and impacts economic growth. This is true even if the estimates are only for the short term. As a result of the data, the coefficients of LPGC, NGC, and CO2 have been shown to be positive and statistically significant, in particular in the short term of the growth model. This finding provides evidence that LPG, NGC, and CO2 contribute to increased GDP. To provide even more specific information, an increase of 1 % in LPGC stimulates GDP by 2.199 % (however, in the long run, it is shown to be unfavorable with limited significance). Furthermore, a one percent increase in NGC leads to a short-term 4.031 % increase in GDP. However, the results show that consumption of other refined products has a negative correlation with economic growth in the short term. When ORPC increases by 1 %, short-term GDP declines by 0.105 %. Similarly, energy consumption contributes to CO2 in the Saudi Arabian economy. To be more explicit, it has been estimated that the short-term elasticity of carbon emissions regarding economic growth is positive and significantly positive. Besides that, the rate of GDP stimulation is increased by 3.617 % for every 1 % increase in CO2. The level of GDP is related to CO2, which is one of the major causes of energy use and is one of the main contributors to CO2. This finding should serve as a call to action for policymakers to develop a plan that reduces energy consumption by mandating the provision of economic incentives for energy conservation to reduce CO2 in the KSA. The estimated value of the lagged error term coefficient, also known as the ECM [CointEq (−1)], is −0.382, which is a negative value. This is significant at the 1 % and 5 % levels of statistical analysis, respectively. This study implies that the adjustment rate towards long-run equilibrium is 38 %, which indicates that the system tries to correct its previous period's disequilibrium at a speed of 38 % during one period of time. The t-statistic is −8.459, and the coefficient is significant. These empirical results refer to a long-term relationship between the KSA's LPGC, NGC, ORPC, CO2, and GDP.

5.3. *Stability of the model*

As part of this study, we put the model through a series of diagnostic and stability tests to establish whether the model specifications are adequate. Table 9 presents the results of the preliminary tests for linear equations, non-normality, serial correlation, and heteroscedasticity. We conduct several tests to explore the aforementioned concerns. At the 5 % significance level, the analysis of the LM test for correlated residues showed that there was no autocorrelation of errors.

Furthermore, the model's R-square value indicates that it might be a good pairing for the observations. In addition, we employ structural stability tests, based on the cumulative sum of recursive residuals (CUSUM) and the CUSUMSQ tests, to validate our findings. Figs. A1 and A.2, respectively, present the empirical results of these two trials. It can be shown from both sets of data that CUSUM and CUSUMSQ fall within the margins of error of any straight line drawn at the 5 % level (represented by the dotted red lines). The model used in this research is robust and policymakers are ready to accept the estimated results.

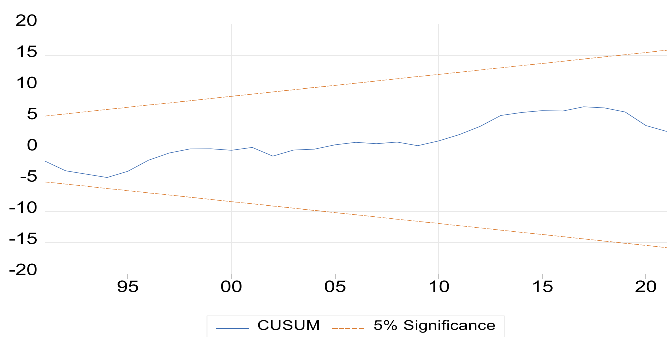

Fig. A1. Plot of CUSUM.

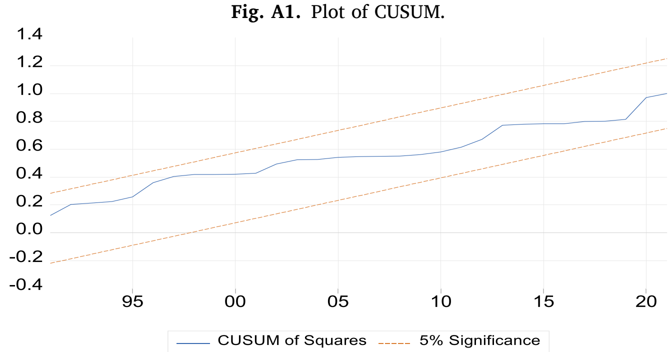

Fig. A2. Plot of CUSUM of Squares

5.4. *Toda-Yamamoto Granger causality tests*

Conventional causality tests, such as the Vector Error Correction Model Granger causality or the Engle and Granger causality tests, have faced criticism due to their limitations and finite sample properties. Research by Toda and Yamamoto [44] and Zapata and Rambaldi (1997) revealed that these approaches are particularly sensitive to nuisance parameter values in small samples, rendering their results somewhat unreliable. Furthermore, within these methods, there is a risk of incorrectly identifying the order of integration of the series (Mavrotas and Kelly, 2001). The Toda and Yamamoto (TY) procedure mitigates these risks by augmenting a vector autoregression (VAR) model in levels with the series' highest order of integration, ensuring that the Wald statistics possess the necessary power properties. This means there is no imperative need to establish the series' order of integration before conducting the causality test. The long-run causality test adjusts the lag order of the VAR based on the highest order of integration, denoted as d_{max}, guaranteeing that Granger causality test statistics adhere to the standard asymptotic distribution (Wolde-Rufael, 2010). To enhance the Wald statistic, the augmented VAR model is estimated using a modified Wald (MWALD) test for the causality examination (Zapata and Rambaldi, 1997). We then use the significance of the first lag(s) to evaluate the causal relationship. Employing this procedure, we estimate the following VAR model using MWALD to discern causal relationships between oil product consumption and economic growth.

The presence of cointegration across variables implies a minimum of three causal links, yet it doesn't reveal the direction in which these interactions are oriented. In a similar vein, the Toda-Yamamoto causality test was used in this investigation to determine whether there is a direct causal link between the series in question. This information helps formulate energy consumption and economic policies that will lead to sustainable development, referring to the economic sector of the Kingdom of Saudi Arabia. The results of the short- and long-run causality tests are presented in Table 10, along with their respective directions. All the F-statistic coefficients are positive and statistically significant when looking at the causality over the long run, which shows that there is a feedback effect between the variables. In considering the above information, the KSA economy direction needs to take into account the leading role that LPGC, NGC, and ORPC play in monitoring the levels of GDP and CO2. The results demonstrate a long-term, unidirectional causal link between the consumption of liquefied petroleum gases and GDP, supporting the growth hypothesis. In addition, we have found that there is a neutral causality from NGC and CO2 to GDP. There is unidirectional causality from NGC to ORPC. The long-term causality test findings indicate that there is causality in both directions, from the consumption of other refined products to GDP. At the same time, there is evidence in favor of the neutrality hypothesis from the data according to the long-run causality results from GDP to NGC. As a result, we discovered evidence that suggests a unidirectional causal relationship between natural gas consumption and the consumption of other refined products. However, estimating the short-term effects of NGC, ORPC, and CO2 results in a negative impact on GDP. We find that these relationships influence each other. This finding is in line with GDP growth projections, which assume that increased EC will improve the current economic situation. In this case, EC would serve as the cause of EG. Without a shadow of a doubt, the oil sector is a major contributor to the Saudi Arabian economy. With its immediate influence on the economic growth of the governorate and its ability to contribute to the long-term expansion of the Kingdom of Saudi Arabia, the energy industry deserves special attention and consideration at every stage of policymaking. This is especially true of the sector's capabilities and the quality of the services it provides. Policymakers in the KSA, actively involved in reducing CO2 while preserving energy consumption, can greatly benefit from the findings of this study. Therefore, policymakers should think about how to make LPGC, NGC, and ORPC more prudent and effective, particularly in the energy sector. Saudi Arabia's government also needs to centralize the renewable energy sector. According to the findings of this study, the only way to ensure stable and long-term economic development is for the Kingdom of Saudi Arabia to select a realistic policymaker and implement modest decarburization and energy-efficiency operations.

6. Conclusion and policy implications

This study makes a significant contribution by investigating the important connection between oil product consumption and economic growth. It does this by looking into the role of liquified petroleum gas consumption, natural gas consumption, and other refined product consumption. Addressing a gap in the existing literature, this paper expands on recent research, particularly in the context of the KSA economy, where no previous study has explored this relationship comprehensively using data spanning from 1970 to 2021. We determined that three relevant series became stationary at the first difference and two other relevant series were stationary through rigorous stationary analyses using ADF and PP unit root tests. Subsequently, co-integration tests confirmed the existence of a long-term association among the variables under consideration. The application of the ARDL methodology further enhanced the depth of this research. The findings indicated that LPGC, NGC, and CO2 exert a positive and significant impact on economic

Table 10
Toda-Yamamoto causality test.

Cause/Effect	Short-run			Long-run	
	Wald statistic	P-value	Cause/Effect	F-Statistic	P-value
lnLPGC→ lnGDP	2.679	0.261	lnLPGC→ lnGDP	7.905	0.001*
lnNGC→ lnGDP	7.167	0.027**	lnGDP→ lnLPGC	0.950	0.394
lnORPC→ lnGDP	10.598	0.005*	lnNGC→ lnGDP	2.342	0.107
lnCO2→ lnGDP	3.795	0.149	lnGDP→ lnNGC	1.615	0.210
lnGDP→ lnLPGC	0.541	0.762	lnORPC→ lnGDP	4.672	0.014**
lnNGC→ lnLPGC	4.411	0.110	lnGDP→ lnORPC	5.280	0.008*
lnORPC→ lnLPGC	1.256	0.533	lnCO2→ lnGDP	2.478	0.095***
lnCO2→ lnLPGC	0.804	0.668	lnGDP→ lnCO2	0.293	0.746
lnGDP→ lnNGC	4.280	0.117	lnNGC→ lnLPGC	2.616	0.084***
lnLPGC→ lnNGC	2.947	0.229	lnLPGC→ lnNGC	0.003	0.996
lnORPC→ lnNGC	5.308	0.070***	lnORPC→ lnLPGC	0.576	0.565
lnCO2→ lnNGC	2.366	0.306	lnLPGC→lnORPC	0.110	0.895
lnGDP→ lnORPC	0.141	0.931	lnCO2→ lnLPGC	0.303	0.739
lnLPGC→ lnORPC	1.419	0.491	lnLPGC→ nCO2	1.786	0.179
lnNGC→ lnORPC	10.619	0.004*	lnORPC→ lnNGC	0.165	0.847
lnCO2→ lnORPC	0.166	0.920	lnNGC→ lnORPC	3.529	0.037**
lnGDP→ lnCO2	1.038	0.594	lnCO2→ lnNGC	2.996	0.060***
lnLPGC→ lnCO2	4.801	0.090***	lnNGC→ lnCO2	1.276	0.288
lnNGC→ lnCO2	1.229	0.540	lnCO2→ lnORPC	0.926	0.403
lnORPC→ lnCO2	0.653	0.721	lnORPC→ lnCO2	1.661	0.201

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

growth both in the short and long term. Hence, energy consumption plays a critical role in driving the increase in CO2 emissions, which is closely linked to the level of real GDP per capita. Similarly, the ORPC coefficient exhibits a positive and statistically significant impact in the short term (although it is insignificant in the long term), indicating that NGC enhances economic growth in the context of the KSA economy. Regarding LPGC and real GDP per capita, the elasticity estimate is positive and significant in the short term. Granger causality analysis has revealed that all ECT coefficients are negative and statistically significant, indicating a long-term feedback effect among the various variables. In the short term, the findings indicate that in the KSA, energy consumption causes economic growth.

In particular, the findings indicate that LPGC, NGC, ORPC, and CO2 all have a considerable influence on economic growth both in the short and long run. Stability tests and diagnostics substantiated the accurate specifications of the estimated models. Empirical results show that all variables, except CO2, have a significant impact on GDP in the short and long term. The VECM Granger causality results indicate a negative and significant GDP coefficient over the long term, indicating the existence of a feedback effect among the relevant variables. We conducted the Granger causality test in accordance with the Toda-Yamamoto procedure and within an enhanced VAR framework, revealed several different causalities. On one hand, we discovered a unidirectional causality between LPGC and economic growth, as well as between NGC and GDP. As a result, there is a causal link that operates in both directions between the consumption of other refined products and GDP. On the other hand, we did not find any connection between the use of natural gas and the emission of carbon, nor did we find any connection between the consumption of natural gas and economic growth. The empirical findings point to the fact that the GDP growth rate reacts to shifts in both the current and lagged values of the independent variable, which further includes the rate of economic growth's own lagged values. The findings reveal a robust first-order autoregressive (lag) impact on economic growth, implying that we can derive the current GDP growth rate from its initial periods. The negative value recommends that GDP during the period firmly retards the display of economic performance. In a related vein, the current values of liquified petroleum gas consumption, in addition to the initial lag values, have a significant impact on the level of GDP. The robustly detrimental impact of lagged LPGC suggests that the value of economic activity in the period immediately preceding the current one, as measured by consumption of liquified petroleum gas, inhibits the economy's capacity to grow in the current period. The study indicates that natural gas consumption (NGC) has a strong influence on Saudi Arabia's economy. This demonstrates that the current use of natural gas has a very clear and significant beneficial influence on the expansion of the entire economy. The findings suggest that using the lagging value of NGC from the first period may enhance performance. Furthermore, the study shows a close relationship between economic growth and both the current and historical levels of other refined product consumption (ORPC). The results signify that at the 10 % level of significance, an increase in the current value of ORPC (other refined product consumption) by 4.0804 % stimulates GDP growth, whereas an increase in the value of ORPC in the past has had variable effects on growth. Therefore, the first period's lagged value of ORPC slows down the current growth performance of Saudi Arabia's economy. The final variable in the model, representing CO2 emissions, has a single lag value. Furthermore, the short-run CO2 elasticity estimates in relation to GDP per capita are both positive and substantial. More specifically, we have demonstrated that a 1 % increase in CO2 levels accelerates economic development by 3.6171 %. In addition, the findings indicate that there is a negative association, at least in the short run, between the consumption of other refined products and economic growth. In the short run, a one percent increase in ORPC will almost certainly lead to a 0.105 percentage point decrease in economic growth. Similarly, energy consumption makes a contribution to CO2 in the Saudi Arabian economy. To be more specific, an increase of 1 % in CO2 emissions promotes a 3.617 % increase in real GDP per capita in the short run. The level of CO2 emissions is proportional to GDP, which is one of the primary reasons for the use of energy and one of the trophic levels of CO2 emissions. This observation should serve as a call to action for policymakers to devise a plan that reduces energy consumption by mandating the provision of economic incentives for energy conservation with the goal of reducing CO2 in the KSA. Therefore, we find evidence of a unidirectional causal relationship between the consumption of natural gas and other refined products. However, after projecting the short-run effects NGC, ORPC, and CO2 cause GDP. These relationships are found to affect each other. This finding is in line with the growth hypothesis, which projects that greater levels of energy consumption will lead to improvements in the economic circumstances that are now in place. Apart from that, economic growth is driven by increased energy use. The energy sector is a great asset to the Saudi Arabian economy. The success of the energy sector directly influences the governorate's economic growth, and policymakers must carefully consider the energy industry's potential to contribute to the future growth of the Kingdom of Saudi Arabia at every stage of the process. This is especially true with regard to the sector's capabilities and the quality of the services it provides. Policymakers in the KSA, actively engaged in slowing CO2 while preserving energy consumption, can greatly benefit from the findings of this study. Thus, policymakers should think about how to make LPGC, NGC, and ORPC more prudent and effective, particularly in the energy sector. Saudi Arabia's government also needs to centralize the renewable energy sector. This analysis suggests that the KSA should adopt a pragmatic policymaker in conjunction with modest decarburization and energy-efficiency initiatives to ensure economic development that is both sustainable and profitable.

Based on our research findings, we propose the following evidence-based policy recommendations tailored to different stakeholders.

1 Policymakers:
  - Implement carbon pricing mechanisms to internalize the environmental costs of CO2 emissions and incentivize cleaner energy alternatives.
  - Establish regulations to promote energy efficiency and encourage investments in renewable energy sources.
  - Develop long-term strategies for transitioning to a low-carbon economy, including support for research and development in clean energy technologies.

2 Industry Leaders:
  - Adopt sustainable practices and technologies to reduce carbon emissions in production processes.
  - Invest in innovation and developing green technologies to enhance competitiveness and mitigate environmental impact.
  - Collaborate with policymakers and stakeholders to advocate for supportive policies and create a conducive regulatory environment for sustainable business practices.

These recommendations, grounded in empirical evidence, aim to facilitate collaboration between policymakers and industry leaders to address the challenges of climate change and promote sustainable development.

CRediT authorship contribution statement

Hounaida Daly: Editing, Conceptualization, Methodology, Writing – original draft, Writing – review & editing, Validation. **Badreldin Mohamed Ahmed Abdulrahman:** Data curation, Validation. **Sumaya Awad Khader Ahmed:** Investigation. **Abderhim Elshazali Yahia Abdallah:** Visualization. **Saeed Hassan Elaageb Hasab Elkarim:** Draft Preparation, Software. **Mastora Sahal Gomaa Sahal:** Writing – review & editing. **Waleed Nureldeen:** Supervision, Software. **Wael Mobarak:** Data curation, Software. **Mona Mohamed Elshaabany:** Supervision, Formal analysis.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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