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Greening the Cityscape: Strategies for Sustainable Urbanization, Low Carbon Emissions, and Robust Economic Growth

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ABSTRACT

This study thoroughly investigates the intricate association concerning urbanization, energy consumption, carbon emissions, and economic growth in Saudi Arabia from 1968 to 2022. Using advanced econometric models and time-series data analysis, we reveal a complex association in which economic growth and urbanization influence energy consumption, leading to increased carbon emissions. The adjustment coefficients for this relationship are estimated to be 0.16%. The causality test findings revealed the existence of both unidirectional and bidirectional causality. Urbanization has a direct impact on both energy consumption and carbon emissions. In turn, carbon emissions affect both energy use and economic growth. Ultimately, carbon emissions influence both energy consumption and economic growth. Our results highlight the urgent need for strategies to reduce carbon emissions by implementing sustainable energy practices, urban planning, and legislative measures. These implications for sustainable development are crucial for Saudi Arabia and offer a structure for other rapidly urbanizing nations dealing with comparable difficulties. Given the potential for change, policymakers must carefully consider and implement these results.

Keywords: Carbon Emissions, Economic Growth, Energy Consumption, Sustainability, Al-Kharj
JEL Classifications: O18; Q51; Q56; R58

1. INTRODUCTION

The United Nations' 2030 Agenda now includes the role of urban areas in sustainable development for the 1st time in their Sustainable Development Goal 11, which focuses explicitly on cities and human settlements, emphasizing their need to be inclusive, safe, resilient, and sustainable. The New Urban Agenda (United Nations, 2016) also highlights urbanization as a catalyst for sustained and inclusive economic growth, social and cultural development, and environmental protection. It also emphasizes the potential of urbanization to significantly contribute to achieving transformative and sustainable development, inspiring us with the possibilities.

Globally, urban regions are grappling with carbon emissions and sustainability challenges. On a global scale, cities are responsible for approximately 75% of worldwide energy usage and 70% of global emissions of greenhouse gases. Urbanization has been responsible for around 10% of the rise in global emissions since 2015, according to the International Energy Agency (IEA, 2024). However, this is not a time for despair but for action. Green techniques in urban development have emerged as a beacon of hope and a critical strategy for addressing these complex issues. Implementing sustainable urban greening initiatives is the key to reducing the environmental impact of cities. These initiatives not only enhance living conditions and support ecosystem services but also offer a glimmer of hope for densely populated areas in developed and developing nations, where green space is often a scarce resource.

One of the most pressing issues of our time is global climate change, primarily driven by the alarming concentrations of greenhouse gases (GHGs) in the atmosphere, a direct result of human activities such as burning coal and fossil fuels. The scientific community has extensively studied this issue, and the findings are alarming. The continuous increase in carbon dioxide emissions is projected to profoundly impact the global climate system, potentially leading to catastrophic outcomes that will affect every aspect of our lives. The international community has prioritized reducing carbon emissions and enhancing environmental quality to avert this crisis.

According to Alam (2006), energy is not just a resource but also the primary force behind all economic activities. Ojinnaka's (2008) study further supports this, presenting substantial evidence that per capita energy consumption is a meaningful predictor of economic growth. However, the challenge lies in maintaining a steady energy supply and using it responsibly for sustainable growth. This is an urgent problem that needs to be addressed. Research indicates densely populated countries like China and India significantly increase carbon emissions to improve economies, raise national incomes, and lessen poverty.

The Kingdom of Saudi Arabia has taken a proactive stance by accepting several international agreements, such as the Paris Agreement and the Kyoto Protocol, to combat climate change and reduce carbon emissions. The potential for environmental harm underscores the urgency of this action if the functional affinity between natural resources and contemporary evolutionary processes is not managed effectively. This is a particularly pressing issue in Middle Eastern nations like Saudi Arabia, where economic expansion, energy security, urbanization, tourism, and environmental sustainability are crucial.

Developing a more environmentally friendly cityscape is a multifaceted challenge that demands an all-encompassing strategy. By adopting green policies, cities can construct more resilient, liveable, and ecologically sustainable urban environments that promote both the long-term sustainability of the planet and the well-being of its inhabitants. This comprehensive approach is both a choice and a necessity in our quest for a sustainable future.

Urban greening strategies, a topic of significant interest in the context of sustainable urbanization, low carbon emissions, and robust economic growth, require a comprehensive approach. Integrating these green practices into urban development is crucial for enhancing the quality of life, promoting ecosystem services, and mitigating city environmental impacts. The initiatives, which involve preserving and creating green spaces, promoting biodiversity, and implementing innovative technologies, can enhance urban resilience and economic prosperity. By prioritizing low-carbon development, cities can reduce their carbon footprint and contribute to global climate goals. The role of green infrastructure, tree conservation, and innovative greening technologies in reducing carbon emissions and fostering health, community well-being, and economic productivity within urban environments cannot be overstated. Therefore, to close our research gap, despite the growing attention towards sustainable urban development, more research is still needed regarding the complex interplay between greening the cityscape, achieving low carbon emissions, and fostering robust economic growth. While individual aspects of this triad have received some attention, comprehensive studies are crucial in bridging the gaps in knowledge and exploring integrated strategies. Many existing studies focus on isolated elements such as green infrastructure or carbon reduction, often overlooking the intricate connections that bind sustainable urbanization and economic prosperity. Holistic examinations that consider the synergies and trade-offs in implementing environmental sustainability and economic development strategies are necessary to address this research gap. Our study is vital to informing policy decisions, urban planning practices, and investment strategies that can genuinely contribute to the Saudi Vision 2030 of resilient and thriving cities like Al-Kharj amidst rapid global urbanization. Closing this research gap is pivotal to guiding cities towards effective and balanced strategies for sustainable urban growth in Al-Kharj.

2. LITERATURE REVIEW

Khan (2023) states that environmental sustainability has grown significantly for developed and developing economies worldwide. Urbanization enables economic expansion and facilitates social change, as observed in developed and developing countries. Constructing high-rise structures and establishing industrial zones are essential for urbanization, significantly contributing to energy consumption and carbon emissions. These urbanization and industrialization activities directly lead to energy consumption and carbon emissions. In their study, Raihan and Tuspekavo (2022) investigated the attainment of environmental sustainability in Malaysia by reducing carbon dioxide emissions. They discovered a significant correlation between economic growth and carbon emissions. More precisely, a 1% rise in economic growth results in a 0.78% rise in carbon emissions. Zi et al. (2016) correlate urbanization and carbon emissions. They explain that the rate of urbanization and the resulting CO_2 emissions vary depending on the season and place.

Murshed et al. (2023) postulated that accelerated economic expansion, increased global trade, and urbanization were causally linked to elevated levels of carbon dioxide emissions. Khan et al. (2022) studied the G7 and E7 nations, examining the relationship between economic growth and population size. It was discovered that economic expansion and population size had a detrimental effect on environmental quality by reducing the "load capacity factor levels." This term refers to the ecosystem's ability to sustain a specific level of economic activity without causing harm to the environment. In the G7 and E7 nations, there is a unidirectional relationship between economic growth, population size, and the load capacity factor. A 1% increase in energy efficiency resulted in a 0.3% long-term increase in carbon productivity, according to a study by Murshed et al. (2022) in seven developing countries between 2007 and 2018. In addition, the analysis indicated that improvements in energy efficiency counterbalance the substantial negative impacts on carbon production caused by financial inclusion, trade globalization, and urbanization in the nations analyzed.

Energy is an essential factor in the economic development of every country. The future expansion of the economy relies on the sustained accessibility of cost-effective energy derived from environmentally sustainable sources. Baz et al. (2022) established a clear correlation between higher energy usage and a decline in environmental quality. The increased utilization of fossil fuels generates carbon dioxide, contributing to global warming and drastically degrading air quality. Consequently, the effort to supply additional energy to enhance economic development has heightened the likelihood of environmental contamination, particularly in the state of the air, increased respiratory ailments and other health concerns. Raihan et al. (2022) contend that energy consumption presents a significant obstacle to attaining environmental sustainability, primarily due to the release of greenhouse gases from non-renewable energy sources. Hence, reductions linked to energy usage are recommended amid the current discussion on sustainability. This reduction is crucial for furthering the goals and objectives of sustainable development. While there is often a direct relationship between higher energy consumption and economic growth, Murshed et al. (2023a) stress the importance of prioritizing the sustainability of this growth.

Yabo and Wang argue that in 2015, the increase in urbanization and economic growth would draw attention to the problem of energy consumption, which could potentially hinder further urbanization and economic progress. Urban regions serve as the economic engines of their countries, experiencing swift growth that leads to increased energy usage and a rise in greenhouse gas emissions. According to Wang et al. (2012), understanding the connection between urbanization and energy use is crucial for energy conservation and emissions reduction. This is a result of the difficulty of decelerating the consumption of fossil fuels while simultaneously sustaining the rate of progress.

Jones's (1989 and 1991) research conducted in 59 developing nations demonstrates that urbanization is the primary determinant of energy consumption. Dahl and Erdogan (1994) conducted similar research and found that urbanization and industry positively impacted energy use. Parikh et al. (1995) discovered a direct correlation between energy use and urbanization. Lenzen et al. (2006) studied Australia, Brazil, Denmark, and Japan. They discovered that the impact of urbanization on energy consumption varied among these nations during the same period.

In their study, Ghosh and Kanjilal (2014) found evidence of a one-way causal relationship between energy consumption, economic activity, and urbanization in India. Shahbaz and Lean (2012) conducted a comprehensive study on the interrelationships between Tunisia's energy consumption and financial development and the impacts of industrialization and urbanization. The research they conducted not only confirmed but further strengthened the conclusions of previous examinations. Urban population growth of 1% is associated with a corresponding increase in energy consumption of 0.9%, indicating a noteworthy and favourable discovery. This finding aligns well with Lui's (2009) and Mishra et al. (2009) findings about the impact of urbanization on energy use.

Furthermore, their study revealed a strong and positive relationship between economic growth and energy consumption. Specifically, for every 1% increase in economic growth, there is a 0.7% increase in energy consumption. Shahbaz et al. (2014) found comparable outcomes in the United Arab Emirates (UAE), whereas Al-Mulali et al. (2013) achieved similar results across the Middle East and North Africa (MENA) countries.

Urbanization has a considerable effect on both energy consumption and carbon dioxide emissions. However, the extent of this influence differs depending on the economic development stage of the region (Li and Lin, 2015). Wang et al. (2016) expressed apprehension about the environmental consequences of urbanization, which has led to an escalation of the energy problem. Consequently, numerous scholars have examined the correlation between urbanization, energy use, and carbon emissions from diverse angles. In a study conducted on a sample of developing countries, Inmaculada and Antonello (2011) discovered an inverted U-shaped curvilinear association between urbanization and CO_2 emissions. Richard et al. (2003) discovered a compelling correlation between carbon emissions and the energy footprint. A unitary elastic relationship was discovered between population, carbon emissions, and energy footprint. Ying et al. (2006) suggested that the influence of population, technology, and prosperity on CO_2 emissions is contingent upon the level of development in a given country. In 2009, Liu conducted a study using factor decomposition models (FDM) and auto-regressive distributed lags (ARDL). The findings indicated that enhancing energy efficiency and accelerating urbanization could contribute to sustainable development. In their study, Zhang and Lin (2012) discovered a rise in energy consumption and carbon dioxide emissions due to urbanization in China.

Using ARDL, FMOLS, and DOLS techniques, Zhang et al. (2021) and Adebayo and Kalmaz (2021) discovered a positive correlation between economic growth and Urbanization and CO_2 emissions. One is for Malaysia, and the other is for Egypt. In their study, Nondo and Kahsai (2020) utilized the ARDL approach to uncover the significant impact of economic growth, energy intensity, and Urbanization on CO_2 emissions in South Africa between 1970 and 2016. In their study, Kirikkaleli and Kalmaz (2020) discovered that economic growth, energy use, and urbanization in Turkey from 1960 to 2016 positively affected CO_2 emissions. They employed FMOLS and DOLS techniques to arrive at this conclusion. In their study, Liu and Bae (2018) highlighted the significant impact of economic growth, energy consumption, and Urbanization on CO_2 emissions in China between 1970 and 2015. They employed the ARDL method to analyze and uncover these positive effects. In a recent study, Islam et al. (2021) highlighted the correlation between economic growth, energy use, urbanization, and CO_2 emissions in Bangladesh.

The relationship between urbanization and carbon emissions has been investigated widely throughout the previous decade, and various econometric methodologies have been used in their research to examine the impact of urbanization on environmental deterioration. However, it is essential to note that these studies have certain limitations. For instance, the data in these studies might need to fully capture the complexity of the relationship between urbanization and carbon emissions. Additionally, the findings need to be more generalizable to other countries or regions due to specific contextual factors. Therefore, our study will identify the interrelationship between carbon emissions, economic growth, energy consumption, and urbanization and suggest a strategy to help policymakers and government organizations implement it for their benefit.

3. METHODOLOGY AND DATA

3.1. Data

This model uses statistical data from British Petroleum (BP) and the World Development Indicators (WDI). BP provides information regarding primary energy consumption (expressed in exajoules) and carbon dioxide emissions (in millions of tonnes) that result from energy usage. On the contrary, World Development Indicators provide the following:

- Data about urbanization, quantified as the urban population
- Insights into economic expansion, quantified as GDP in constant US dollars.

The research spans a significant period, from 1968 to 2022, to ensure a comprehensive analysis of past events. This extensive duration allows for thoroughly examining the short-term and long-term relationships among the variables under investigation.

3.2. Model Specification

The present study was meticulously designed to develop a comprehensive strategy for investigating the interrelationships among carbon emissions, economic growth, energy consumption, and urbanization in the context of Saudi Arabia at a macro level. The outcomes of this model will be implemented at a micro level in the Al-Kharj region for its sustainable development. Hence, the model can be formulated as:

Carbon emissions = f (Economic growth, Energy consumption, urbanization)

It is crucial to understand that several studies (Khan et al., 2022a; Murshed et al., 2022; Khan et al., 2022) have emphasized normalizing data series before employing an econometric model. By implementing a natural logarithmic transformation on every variable in our research, we can ensure that all measurements remain consistent, thereby avoiding potential challenges associated with distributional characteristics. This method establishes stationarity in a series of variables. It presents an exciting possibility when examining indices such as carbon dioxide emissions from energy, primary energy consumption, and other variables represented by different units. Therefore, each variable is effectively employed and converted into a logarithmic function, underscoring the importance of stationarity in econometric modelling. Thus, all the parameters are used in a real term and converted into a logarithmic function:

$$LYt = log\ (Yt) \tag{1}$$

This can also be constituted in a log-linear econometric structure as:

$$log\ (Carbon\ emissions)\ t = \beta_0 + \beta_1\ log\ (energy\ consumption)\ t + \beta_2\ log\ (economic\ growth)\ t + \beta_3\ log\ (urbanization)\ t + \varepsilon_t \tag{2}$$

Where β_0: Constant term, β_1: Coefficient of a variable (energy consumption), β_2: Coefficient of variables (economic growth), β_3: Coefficient of variables (urbanization), t: Time trend, and ε_t: Assumed that the random error term is usually uniformly and autonomously distributed.

The Long-run model can be expressed as:

$$LNC_t = a_0 + a_1\ LNE_t + a_2\ LNG_t + a_3\ LNU_t + \varepsilon_t \tag{3}$$

In the short run, our model can be expressed as follows:

$$lnc_t = \quad + \sum_{i}^{k} = 1\beta_i lnc_{t-i} + \sum_{j}^{k} = 1\varnothing_j lne_{t-j} + \sum_{m}^{k} = \omega 1\partial_m lng_{t-m} + \sum_{n}^{k} = 1\theta_n lnu_{t-n} + u_{1t} \tag{4}$$

LNC represents the lag value of carbon emissions, LNG represents economic growth, LNE represents the lag value of energy consumption, LNU represents the log value of several urbanizations, ω is the coefficient, and u represents the error.

Stationarity tests, a complex yet essential aspect of econometrics and statistics, are commonly used to determine the order of integration for each variable within a system. A wide range of tests, each with its intricacies, are used in analytical and empirical research to assess the integration order, considering various factors. In our systematic empirical stationarity analysis, we will delve into the complexities of the Augmented Dickey-Fuller (ADF) and Phillips-Perron tests while considering intercepts. After the unit root test, we will proceed with the co-integration test by Johansen co-integration. If the co-integration is present, we will proceed with the Vector Error Correction Model (VECM). If not, we will use the Vector Autoregressive Model (VAR). If co-integration is present, we will go for the further estimation of long-and short-term estimates; the error correction term can be estimated as:

$$ECT_{t-1} = [Y_{t-1} - \eta_j \chi_{t-1} - \xi_m R_{t-1}] \tag{5}$$

Furthermore, this study employs the vector error correction model framework to ascertain the causal direction among lnc, lne, lng, and lnu. Equation 6 examines the causal relationship between the variables under consideration. Where ECT represents the error correction term, σ represents the first difference, and ϕ represents the white noise residual ∂, which signifies the direction of short-term causality. Figure 1 provides a clear and comprehensive flow chart of the analytical techniques employed in the study, ensuring you are reassured about the clarity of our methodology.

$$\sigma \begin{bmatrix} lnc_t \\ lne_t \\ lng_t \\ lnu_t \end{bmatrix} = \begin{bmatrix} \theta_1 \\ \theta_2 \\ \theta_3 \\ \theta_4 \end{bmatrix} + \sum_{n=1}^{m} \sigma \begin{bmatrix} \partial_{11} & \partial_{12} & \partial_{13} & \partial_{14} \\ \partial_{21} & \partial_{22} & \partial_{23} & \partial_{24} \\ \partial_{31} & \partial_{32} & \partial_{33} & \partial_{34} \\ \partial_{41} & \partial_{42} & \partial_{43} & \partial_{44} \end{bmatrix} n \begin{bmatrix} lnc_{t-n} \\ lne_{t-n} \\ lng_{t-n} \\ lnu_{t-n} \end{bmatrix} + \begin{bmatrix} \omega_1 \\ \omega_2 \\ \omega_3 \\ \omega_4 \end{bmatrix} \left[ECT_{t-1}\right] + \begin{bmatrix} \varphi_1 \\ \varphi_2 \\ \varphi_3 \\ \varphi_4 \end{bmatrix} \tag{6}$$

4. RESULTS

A comprehensive descriptive statistics analysis and correlation coefficient matrix are displayed in Table 1. The matrix emphasizes the following four variables: Urbanization (LNU), economic growth (LNG), carbon emissions (LNC), and energy consumption (LNE). The "Mean" denotes the arithmetic average of each variable; LNU is 16.3, LNC and LNE are both 5.4, and LNG is 26.6. The "Median" denotes the central values of the datasets, which correspond approximately to the norms of LNG (26.6) and LNE (5.4). In contrast, LNU has a median score of 16.5, whereas LNC has a marginally higher median score of 5.5. The terms "Minimum" and "Maximum" denote the upper and lower limits of the observations within each dataset. As an illustration, the LNU dataset spans from 14.7 to 17.2, whereas the LNC dataset spans from 4.1 to 6.5. The final statistical metric, standard deviation, measures the degree of dispersion or variation relative to the mean. The values in this instance vary between 0.28 (LNE) and 0.75 (LNC), signifying distinct degrees of dispersion among the datasets. The analysis of the correlation coefficient matrix indicates that the variables exhibit a strong positive coefficient correlation. Table 1 presents a comprehensive summary of each variable's central tendency, variability, range of values, and correlation matrix, furnishing abundant information about the dataset's attributes.

Table 2 shows the results of the unit root test, which is a part of the Augmented-Dicky Fuller test and the Phillips-Perron test, which are used to figure out if the series is stationary or not and at what level, i.e., at I (0), I (1) and I (2) level. The series for carbon emissions from energy stopped changing at I (1) levels for both tests. This means the series for carbon emissions has become stationary at the first level. Moreover, a similar finding exists for energy consumption and economic growth. Furthermore, the urbanization series became stationary at I (0) levels by the Phillips-Perron test. However, the ADF indicates that the series became stationary at the second level, further supported by the PP test. This shows that the series has reached a point where it is stationary at the second order of difference. Due to this second order of difference, we will not use the ARDL bound test.

Following the unit root test, we delve deeper into the models using a second-order lag. Table 3 showcases the results of the Johansen co-integration test, a pivotal step in our analysis. The asterisk (*) mark indicates that at least one series has a co-integration, which denotes both long-term and short-term effects. This finding paves the way for the vector error correction model (VECM), a powerful tool in our analysis, demonstrating our research's practical relevance and applicability.

The significant co-integration test result at the 0.05 level indicates the presence of both short-run and long-run connections between carbon dioxide emissions from energy, primary energy consumption, economic growth, and urbanization. The normalized co-integrating coefficient succinctly captures this relationship as:

$$lnc=0.65\ lne+0.29\ lng+0.71\ lnu$$

Our objective is to examine whether the long-term changes in carbon dioxide emissions from energy (*lnc*), energy consumption (*lne*), economic growth (lng), and urbanization (*lnu)* positively and statistically significantly influence this variable. The results have significant implications: A 1% increase in energy consumption corresponds to a 0.65% increase in carbon dioxide emissions from energy. Similarly, urbanization exhibits a comparable impact, leading to a 0.71% point increase in urban-related carbon dioxide emissions for every percentage of urban growth. Notably, carbon dioxide emissions from economic growth display a positive correlation with carbon consumption, indicating that a percentage change in economic growth leads to a change in carbon emissions level by 0.29%. These findings, supported by Johansen's co-integration test, underscore the urgent need to address these factors to mitigate carbon dioxide emissions.

The error correction coefficient, a vital measure of the model's precision, gives the speed of adjustments with which the model will restore its equilibrium following any disturbances. The coefficient

Table 1: Descriptive statistics and correlation coefficient matrix

Variable	Mean	Median	Max.	Minimum	Standard deviation	LNC	LNE	LNG	LNU
LNC	5.4	5.5	6.5	4.1	0.75	1			
LNE	5.4	5.4	5.8	4.8	0.28	0.98	1		
LNG	26.6	26.6	27.4	25	0.52	0.88	0.8	1	
LNU	16.3	16.5	17.2	14.7	0.73	0.98	0.93	0.9	1

Table 2: Unit root test

Variable	Level	ADF		Phillips-Perron	
		t-statistic	Probability	Adj. t-stat.	Probability
LNC	I (0)	−0.93	0.77	−1.03	0.74
	I (1)	−8.13	0.00*	−8.37	0.0*
LNE	I (0)	−0.71	0.83	−0.63	0.85
	I (1)	−8.54	0.00*	−8.61	0.0*
LNG	I (0)	−3.27	0.02**	−2.83	0.06
	I (1)	−5.2	0.0*	−5.3	0.0*
LNU	I (0)	−2.56	0.11	−12.9	0.0*
	I (1)	−1.34	0.6	−1.02	0.74
	I (2)	−6.03	0.0*	−3.5	0.01*

*, **represents 1 and 5% significance level source; Authors computation

Table 3: Johansen Co-integration Test for LNG as a dependent variable

Parameter	Eigenvalue	Trace statistics	0.05 critical value	Probability**	Max-Eigen statistics	0.05 critical value	Probability**
None*	0.56	69.4	47.86	0.0002	42.95	27.58	0.0003
At most 1*	0.28	26.45	29.8	0.12	17.13	21.13	0.17
At most 2	0.11	9.32	15.49	0.34	6.42	14.26	0.56
At most 3	0.053	2.90	3.84	0.09	2.9	3.84	0.09
LNC			**LNE**		**LNG**		**LNU**
1			−0.65		−0.29		−0.71
			0.14		0.06		0.112

**MacKinnnon-Haug-Michelis (1999) P-values

Source; Authors computations

of ECT with *lnc* as a dependent variable is negative and statistically significant, indicating a convergence from short dynamics towards long-run equilibrium. The adjustment coefficients are 0.16%, respectively, towards long-run equilibrium in a disequilibrium situation, further reinforcing the robustness of our model.

Short-term changes ultimately lead to long-term balance. The statistically significant and negative coefficients for economic growth, urban expansion, carbon dioxide emissions from energy use, and primary energy consumption support this. In cases of prolonged imbalance, the adjustment coefficients were 0.16%. The short-run equation model can be represented and written using the following notation:

$$\Delta lnc_t = -0.16\,ECT_{t-1} - 0.11lnc_{t-1} - 0.01lne_{t-1}$$
$$-0.16lng_{t-1} + 0.84lnu_{t-1} + 0.02$$

With a negative ECT, we can infer that primary energy consumption, economic growth, and carbon emissions from energy use all have a long-run causal relationship. A negative sign for the coefficient indicates the ability to return to equilibrium. According to the short-run coefficient, there was an increase in carbon emissions from the previous year. Carbon emissions are expected to rise by 1.1%. As primary energy consumption rises, carbon emissions from power plants will also increase by 1%. For every percentage point of economic growth, carbon emissions from the energy sector will increase by 1.6%, and urban growth in the short run reveals a decrease in carbon emissions of 8.4%. This might be due to sustainable urban planning.

When we do the analysis, we will also use the fully modified ordinary least squares (FMOLS), dynamic ordinary least squares (DOLS), and Canonical Cointegration Regression (CCR) methods for co-integration regression. This will make our results even more reliable. These methods are frequently employed in econometrics to examine the enduring connections between variables. The findings of a co-integration regression analysis using FMOLS, DOLS and CCR methods are presented in Table 4. The dependent variable in this analysis is carbon emissions. The model aims to elucidate the relationship between carbon emissions and other variables. Within this framework, the variable in question is the dependent variable. The regression model includes independent variables such as energy consumption, economic growth, urbanization, and carbon emissions. They are indicators of variables that could impact carbon emissions.

Table 4: Robustness check by co-integration regression

Variable	FMOLS		DOLS		CCR	
LNE	1.29	0.00	1.25	0.00	1.31	0.00
LNG	0.16	0.00	0.24	0.00	0.15	0.00
LNU	0.44	0.00	0.28	0.00	0.44	0.00
C	−13.04	0.00	−12.3	0.00	−12.9	0.00
Adj R^2	0.99		0.99		0.99	
Jarque-Bera	2.71	0.26	1.78	0.41	1.48	0.48

C: Co-integration coefficient deterministic; *Represents 1% of significance level
Source: Author computation

Our significant statistical findings reveal that the energy consumption coefficient is 1.29. This suggests that a carbon emission increase of 1.29 units is associated with every one-unit increase in energy consumption. The coefficients for economic growth (0.16) and urbanization (0.44) both indicate positive correlations. The constant term (C) is −13.04, a concerning value. Importantly, all exogenous variables are significant at the 1% level, providing robust evidence for our analysis.

Our findings continue to underscore the positive correlation between the variables. The energy consumption coefficient is 1.25, suggesting a direct relationship. The coefficient associated with economic growth is 0.24, indicating a positive correlation with the variable of interest. Similarly, the coefficient for urbanization is also positive, at 0.28. All exogenous variables are statistically significant at the 1% significance level, with the constant term (C) having a value of −12.3. These results emphasize the urgent need to address these issues.

According to the CCR coefficients, the energy consumption coefficient is 1.31, indicating a positive correlation. Given that the coefficient for economic growth is 0.15, there is a positive correlation between the variable of interest and the coefficient for urbanization (0.44). All exogenous variables investigated in this study are statistically significant at the 1% level, meaning they strongly influence carbon emissions. The constant term (C) is −12.9, indicating the expected value of carbon emissions when all other variables are zero, which is harmful.

The robustness of our model is evident in the high R-squared and adjusted R-squared values (0.995 and 0.994 for CCR, 0.998 and 0.997 for DOLS, and 0.995 and 0.994 for FMOLS). These values indicate that the independent variables can explain a significant portion of the variation in carbon emissions, demonstrating a solid fit of the model to the data. The Jarque-Bera test further underscores the importance of our findings.

Figure 1: Flow chart of the analytical techniques employed in the study

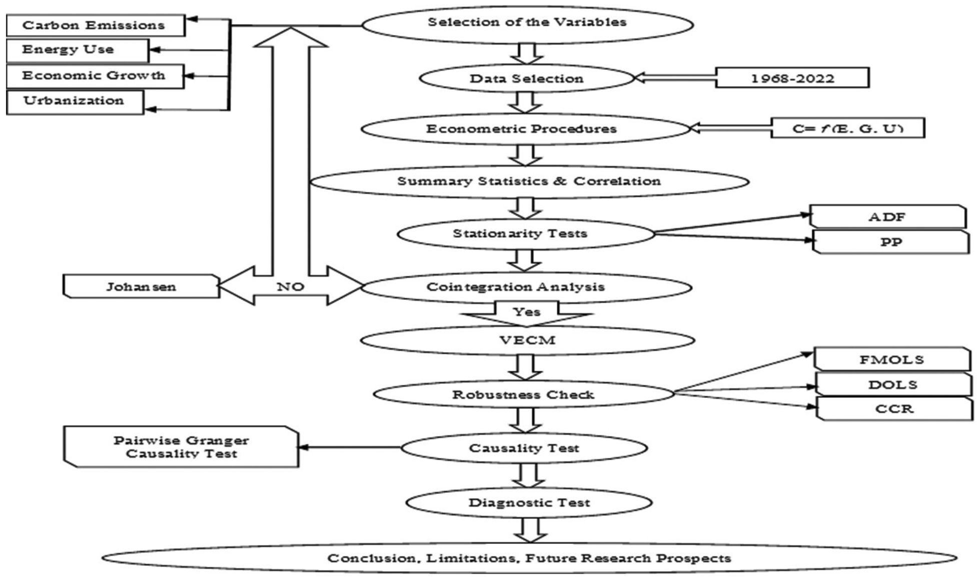

Figure 2: Depicts the granger causality test, where *and ** represent the 5% and 1 % significance levels, respectively

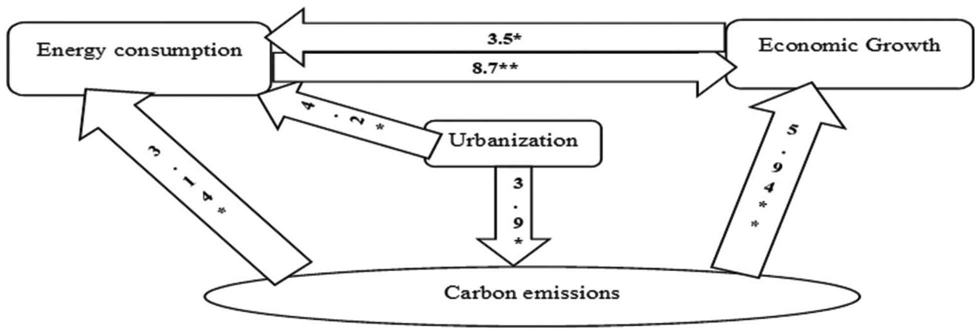

Figure 2 visually represents the pairwise Granger causality test results, revealing both unidirectional and bidirectional causality. A key finding is the unidirectional relationship between carbon emissions, energy consumption, and economic development. We also identify a bidirectional causal relationship between energy consumption and economic growth. Furthermore, a unidirectional causal relationship exists between urbanization carbon emissions and energy consumption. The significance of the Breusch-Godfrey serial correlation LM test, the Breusch-Pagan-Godfrey heteroscedasticity test, and the Jarque-Bera normality test cannot be overstated. These tests are crucial in validating our analysis, confirming the absence of serial correlation and homoscedasticity and the normal distribution of the series, and instilling confidence in the reliability of our findings.

5. CONCLUSION

Global concerns regarding climate change and the associated adversities have manifested the necessity for achieving environmentally sustainable growth by phasing out the traditional trade-off between economic gains and environmental losses. In this regard, reducing carbon emissions has become a significant concern worldwide. Although the issue of establishing low-carbon economic growth has been widely acknowledged in the Paris Agreement and the SDG declarations of the United Nations (Murshed et al., 2022), not much emphasis has been devoted to the literature on identifying the macroeconomic factors influencing the level of carbon emissions. Hence, this current study attempted to evaluate the effects of energy consumption, economic growth, and urbanization on the carbon productivity levels in Saudi Arabia and in the Al-Kharj Municipal Region, a region known for its rapid urbanization and significant contribution to the country's carbon emissions. In addition, further addressing the literature gap and if energy efficiency gains indirectly influence carbon productivity levels by moderating/mediating the impacts of other macroeconomic factors on carbon productivity, this study also focused on unearthing and estimating these effects. Therefore, the present study was meticulously designed to develop a comprehensive strategy for investigating the interrelationships among carbon emissions, economic growth, energy consumption, and urbanization in the context of Saudi Arabia at a macro level spanning 1968-2022.

Our findings on the harmful energy consumption-CO_2 emissions tightening (ECT) indicate a long-term causal relationship between primary energy consumption, economic growth, and carbon emissions from energy use. Importantly, these findings offer hope. The negative coefficient suggests a tendency to return to equilibrium, implying that we can steer these factors towards a more sustainable path with the right interventions. The short-term coefficient, however, shows a rise in carbon emissions from the previous year, projecting an increase of 1.1%. As primary energy consumption increases, carbon emissions from power plants are expected to rise by 1%.

Similarly, for every percentage point of economic growth, carbon emissions from the energy sector are projected to increase by 1.6%. However, amidst these projections, short-term urban growth indicates an 8.4% decrease in carbon emissions, possibly due to sustainable urban planning. This finding underscores the potential for change and the importance of sustainable practices in our urban areas, instilling optimism for the future.

Furthermore, we conducted a robustness test using co-integration regression analysis by FMOLS, DOLS, and CCR. These regression analyses reveal that energy consumption is the most common, urbanization is second, and economic growth stands last in causing carbon emissions. At the end, we conduct a pairwise Granger causality test to reveal the direction of causality, indicating both unidirectional and bidirectional. The relationship between carbon emissions and energy consumption is one-way causation, a robust finding supported by Al-Dhubaibi et al. (2024). Furthermore, the one-way link between carbon emissions and economic growth, which is supported by Bah and Azam (2017) and Ali et al. (2017), and the two-way link between energy use and economic growth, which was found and supported by Malik (2021), Yuan et al. (2007), and Belloumi (2009), make our research even more reliable.

The results of the Breusch-Godfrey serial correlation LM test, the Breusch-Pagan-Godfrey heteroscedasticity test, and the Jarque-Bera normality test all show that our research method is robust. These tests confirm the absence of serial correlation, or homoscedasticity, and the normal distribution of the series. This further strengthens the validity of our findings on the unidirectional causal relationship between urbanization, carbon emissions, and energy consumption.

5.1. Limitations and Future Research

The findings of this study, delving into the dynamic interplay of economic growth, energy consumption, and urbanization on CO_2 emissions in Saudi Arabia, could have significant implications for the fields of environmental economics and econometrics. This study could act as a launching pad for further research in developing countries, employing different econometric models. Additionally, future research could delve into growth determinants that still need to be addressed, such as forested areas, agricultural productivity, globalization, technological innovation, trade openness, financial development, foreign direct investments, industrialization, and more. While this study focused on carbon dioxide emissions as an indicator of environmental degradation, future studies could explore other measures, such as consumption-based carbon emissions or other environmental emissions like nitrous oxide (N_2O), sulfur dioxide (SO_2), methane (CH_4), carbon monoxide (CO), ground-level ozone (O_3), hydrogen sulfide (H_2S), and other short-lived climate forces (SLCF), to further enhance environmental quality in Saudi Arabia.

Although carbon dioxide emissions are a crucial indicator of environmental degradation, they are not the sole cause of environmental pollution. This study could be enriched by incorporating more environmental pollution indicators, such as water and land pollution, in future research on Saudi Arabia. Furthermore, future research could compare country-specific results to overall panel outcomes using advanced econometric methodologies and panel estimations. These comparisons could offer valuable insights, emphasizing the necessity for a more comprehensive understanding of environmental degradation.

5.2. Recommendations

Redirecting investments towards more miniature cities and towns, which still need to be saturated with job creation and congestion, holds immense potential. Our study strongly advocates for a shift from Riyadh to the Al-Kharj region. This moves promises to relieve the strain on megacities and foster more balanced regional development, instilling a sense of optimism for a brighter future.

Implementing and spreading automated energy control systems in the residential sector is crucial for energy conservation. However, it is equally important to underscore the pivotal role of public knowledge and effective policies. We can significantly reduce energy usage and emissions by promoting awareness and implementing policies that encourage energy conservation. This, coupled with adopting zero-emission buildings as the standard, can empower us to shape a more sustainable future.

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