Drivers of Renewable Energy Use in Saudi Arabia: Evidence from Wavelet Local Multiple Correlation Approach

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ABSTRACT

This study examines the impact of various factors, including oil rents, government effectiveness, economic complexity, and economic growth, on the use of renewable energy in Saudi Arabia. Employing a novel time-localized wavelet multiple regression correlation framework, the unique approach followed reveals significant and positive interconnections between these factors and promotes renewable energy utilization in the long run. However, the aforementioned factors' short-term correlations are substantially lower and insignificant for some time intervals. Importantly, the analysis performed shows that oil rents and government effectiveness play a dominant role among the other factors. These findings have crucial policy implications, highlighting the need for effective governance and the potential for diversifying energy sources in Saudi Arabia.

Keywords-renewable energy; oil rents; economic growth; economic complexity; time-localized wavelet correlation

I. INTRODUCTION

Governments are faced with multidimensional ecological challenges and energy insecurities and are forced to adopt new development strategies. On the one hand, there is a pressing need to reduce energy consumption and find new Renewable Energy (REN) sources. Therefore, during the last decades, governments, professionals, and academics in energy economics have paid great attention to the potential drivers of the development of REN, which is perceived as one of the pillars of the economic and strategic plans of most countries [1]. However, looking at the current situation, most economies have not made significant progress toward the transition to REN, which requires substantial effort to identify and reduce impediments to the transition process [1]. Those impediments include political and institutional stability [2], financial development [2, 3], corruption [4-6], governance [1, 7, 8], human development [9], quality of institutions, and income inequality [2, 10]. The main aim of this paper is to check the relevance of government effectiveness, economic complexity, economic growth, and oil rents as drivers of REN use. Specifically, the following question is asked: To what extent and how do these factors shape the REN pattern? A reference to the context of Saudi Arabia, an oil-rentier country, is made using an innovative empirical strategy based on the novel Wavelet Local Multiple Correlation regression (WLMC) [11]. Six reasons motivated this investigation.

First, during the last COP27 Climate Change Conference (December 2022), Saudi Arabia pointed out the continued efforts to enhance REN's potential as one of the pillars of its 2030 strategic vision. While Saudi Arabia is the third most oil dependent economy in the world, earning more than 80% of its export income through oil (2022), Saudi Arabia has considered diversifying its energy mix through investments in green technologies and technologies and profiting from the natural abundance of wind and sunlight [12, 13]. In this regard, Saudi Arabia has launched its National Renewable Energy Plan (NREP) as a road map to persist the efforts toward a Circular Carbon Economy (CCE). The latter aims to generate 3.45 gigawatts (GW) by renewable energy sources by 2020, 9.5 GW by 2023, and to convert 50% of its domestic energy supply to REN by 2030. In 2024, 22.8 GW of REN projects are under different stages of development, including 2.8 GW that will be operational before the end of the year, according to the plans of the Ministry of Energy: Renewable Energy Policies. In line with the 2030 National Vision, the government instituted the Saudi Green Initiative (SGI) as an agenda for the "Green Transition," with the purpose of increasing the use of REN as a part of its domestic energy mix, reducing CO_2 emissions by more than 278 megatons per year, and helping cut methane emissions by 30% before 2030 within the Global Methane Pledge (GMP) [14]. Despite the tremendous predisposition of Saudi Arabia to the development of REN potential, little is known about the main drivers of its development. Several driving factors in the REN literature related to oil-rentier economies, such as Saudi Arabia, have yet to be explored. The present paper attempts to fill this gap.

Second, in terms of economic complexity, the REN-economic complexity relationship has recently been tackled in the literature [15-18]. However, this relationship is still convoluted, and two main arguments are competing. On the one hand, economic complexity, as measured by the economic complexity index, quantifies the technologically intensive export composition of an economy [19]. Greater levels of economic complexity entail a higher demand for energy due to increased diversification of manufactured products and intensification of production, which in turn discourages the use of REN in favor of fossil fuels in an energy-intensive economic framework. This argument has been evidenced by several scholars, including, among others, [15, 18]. On the contrary, higher economic complexity may help develop REN through the production mix, encouraging the use of clean technologies and the integration of clean energy sources into the production process, reducing carbon emissions, and increasing the usage of REN [20]. The present study falls within this research course and supplements previous research by checking the relevance of economic complexity in shaping the REN pattern in Saudi Arabia.

Third, in addition to economic complexity, government effectiveness is another crucial factor that can drive the use of REN. There are several reasons why these two variables are interconnected. Governments can adopt a win-win strategy in areas with high environmental degradation by incentivizing cleaner production and penalizing fossil-based energy resources [21]. Governments can also boost REN production by promoting low-carbon production processes and minimizing the complexities of the energy transition stage [22]. Similarly, government effectiveness can significantly stimulate the energy transition through low corruption, stable economic policies, and high-quality institutions [6]. This study examines whether government effectiveness contributes to developing REN use in Saudi Arabia's economy.

Fourth, two of the most frequently explored drivers of REN are economic growth and oil rents. It is well acknowledged that the oil rent-REN nexus is receiving more attention in the energy literature not only due to its prominence, but also for its joint interconnections with other drivers, such as economic growth [23-25]. Studies in literature are extremely abundant but have different or conflicting outcomes. Literature is separated into two dynamics. The first concerns the economic growth-REN relationship, whereas the second shifts the focus to oil-REN connectedness. Several arguments are underlying the economic growth-REN nexus. A booming economy can help speed up the REN transition process in several ways. Having robust financial systems can facilitate the generation of funds and investments in new sectors, such as green technologies and renewable product systems, which can improve the usage of REN and accelerate the transition process to a REN economy [23, 26, 27]. Thus, sustainable economic growth alleviates the conversion from traditional non-renewable energy production resources to technology-based renewable sources. Moreover, sustainable economic growth increases the anxiety about the non-REN sources, empowering the shift to REN usage. In addition, governments would be better placed in booming economies if they make sacrifices to encourage REN production and usage. People in wealthier economies are more likely to exhibit environmental concerns and may be willing to use and invest in REN [26]. For oil rents, several arguments explain how oil rents and REN are connected. For countries relying on imported energy, an increase in oil prices may positively impact REN since it encourages more investments in clean sources. Moreover, rising oil prices will compel governments to search for more advanced and efficient energy sources. The ongoing Russo-Ukrainian war is an illuminating example; European countries are actively seeking for alternative energy sources and restarting their suspended nuclear units. Similarly, higher oil prices alleviate concerns about energy costs and make people more aware of oil substitutes such as REN [28]. However, oil-rentier countries like Saudi Arabia are weary of their competitive advantage in the energy markets. It could be claimed that these countries have little incentive to switch to REN for their energy production and use. These countries are not motivated to develop their renewable energy strategies unless their oil reserves decrease, renewable energy production costs decrease, or a government policy is imposed at the national or international levels [29]. Therefore, Saudi Arabia is a good illustration. The Saudi government established its NREP and inaugurated the Saudi Green Initiatives in 2021, uniting environmental protection, energy transition, and sustainability programs to reduce carbon emissions and increase renewable energy usage. However, Saudi Arabia is facing challenges, as decision makers fear the transition to conventional renewable energy, since huge investments and skills in know-how in R&D, innovations, and technology are required [30].

Fifth, this study differentiates itself from previous works focused on REN drivers, by deploying the novel WLMC analysis [11]. Several reasons are counted for implementing WLMC. First, the main weakness of the bivariate wavelets is that they cannot account for the interaction of more than two variables in the time-frequency domain. Second, employing a standard bivariate wavelet tool results in many pairwise wavelet plots, which may complicate the information generated to offer pertinent policy implications. Also, it can lead to experiment-wise error rate inflation and several wavelet scales, which can lead to spurious correlations. Additionally, using multiple and partial wavelets allows the exploration of the connectedness between two or more variables in the time-frequency domain, and partial wavelets will enable the study of the connection between two variables after cancelling the effect of the third variable. Clearly, partial wavelets are helpful in showing how multiple time series interact over time scales and frequencies. However, researchers cannot identify the "dominant variable" and its effect on the dependent variable. Finally, most existing studies cannot isolate the "dominant variable" due mainly to the absence of an appropriate tool. Thus, the present study closes this gap. The WLMC is employed within a multi-setting perspective (bivariate, tri-variate, four-variate, and five-variate settings) to better understand the driver-REN connectedness over time scales and frequency periods.

Furthermore, despite the extensive research on the factors that drive the use of REN, there remains a literature gap and a significant scarcity of research on the drivers of the REN utilization in an oil-producing country. A brief review of previous works related to REN drivers is reported in Table III in the Appendix. This study aims to fill the gap in the existing literature in several ways. First, unlike prior research work, the present study investigates the individual and joint impact of economic complexity, economic growth, oil rents, and government effectiveness on REN usage in Saudi Arabia. This is the first study to take into account these factors separately and jointly when analyzing the REN pattern. Second, it identifies the time-frequency linkages between the selected drivers and REN using the novel WLMC. Apart from its novelty, the WLMC allows us to investigate the drivers-REN usage nexus within a bivariate and multivariate setting and to identify the "dominant" drivers. Third, the study refers to recent data covering the period 1996-2022 to provide the readers with fresh insight and a deeper understanding of how drivers shape the pattern of REN.

This study offers a significant contribution to the existing literature in several ways. It introduces a unique tool, the WLMC, which enables the identification of the primary drivers of REN usage in Saudi Arabia. The empirical testing performed demonstrates how the differential and combined effects of each driver on REN usage can be assessed and how the most dominant variable among all the selected drivers can be pinpointed. The findings of this study can be transferred to other countries to identify the key determinants that impact the development of renewable energy, especially in oil-rich exporting countries. Finally, this study serves as an excellent starting point for researchers looking to explore the complexities of REN drivers in the time-frequency domain.

II. DATA AND METHODS

A. Data Description

The current study employed annual data for Saudi Arabia covering the period 1996-2022. The availability of data limited this time period. This study resorts to the government effectiveness index (GE) as defined by the World Bank database [31]. This index reflects perceptions of the quality of public services and the civil service and the degree of their independence from political pressures, the quality of policy design and implementation, and the credibility of the government's commitment to such policies. The government effectiveness metric represents a country's score on the aggregate indicator, in units of a standard normal distribution. Government effectiveness time series were collected from the Trading.com database [32]. Total REN consumption approximates the REN usage as a percentage of the total final energy consumption. The data were collected from the Climate-Watch database [33]. Gross Domestic Product (GDP) growth rates (EG) were sourced from the World Bank database [31]. Regarding oil rent (RENT), this work refers to it as a percentage of GDP published by the World Bank [31]. Regarding economic complexity (EC), the economic complexity index designed on a country basis by the GrowthLab of Harvard University is selected [34]. The underlying idea of the economic complexity index is that higher diversified economies tend to diversify their exports on average and have low ubiquity simply because only a few economies can produce these sophisticated goods [35]. Conversely, less sophisticated economies tend to produce few ubiquitous products. Based on inherent changes in export diversities and the ubiquity levels, [19] created a measure of a country's productive structure that integrates information concerning the sophistication of the export products. The time series used, their abbreviations, and their sources are given in Table I. The descriptive statistics of the time series are portrayed in Table II.

TABLE I. DESCRIPTION OF VARIABLES, ABBREVIATIONS, AND SOURCES

Variable	Symbol	Description	Source
Government effectiveness	GE	A measure of the quality of public services, the civil service, and the degree of its independence from political pressures.	[32]
Economic complexity	EC	Metric of the productive capacity and sophistication of exports.	[34]
Renewable energy	REN	Total energy generation from various renewable sources, as a percentage of total energy consumption	[33]
Economic growth	EG	GDP growth rate	[31]
Oil rent	RENT	Oil rents as a percentage of GDP	[31]

TABLE II. DESCRIPTIVE STATISTICS

	EG	RENT	GE	EC	REN
Maximum	0.112	0.541	0.465	0.820	0.030
Minimum	-0.041	0.160	-0.390	-0.870	0.005
Mean	0.020	0.340	-0.048	-0.008	0.009
SD	0.038	0.106	0.233	0.471	0.006
Skewness	-0.109	0.052	0.295	-1.101	2.798
Kurtosis	2.1922	2.8187	2.168	2.192	9.625
J-B	1.75**	2.551*	2.125*	1.758*	81.34***

SD stands for standard deviation, and J-B stands for Jarque-Bera normality test. The superscripts *, **, *** denote the significance at 10, 5 and 1% levels, respectively.

The statistics in Table II display that the EC exhibits the highest volatility measured by SD, whereas the REN has the lowest SD. The GE and EC time series are slightly skewed to the left, whereas the other variables are skewed to the right. The kurtosis reveals that the REN manifests the greatest platikurtic. The J-B test is significant for all the time series, showing a substantial departure from the normal distribution

(Figure 1). Several comments emerge from the correlation coefficients. EC is significantly and positively correlated with the GE and REN usage, but negatively associated with EG and RENT. Furthermore, EG is strongly and positively correlated with RENT. GE is positively and significantly correlated with the use of REN and negatively associated with oil dependency. RENT and REN usage are significantly and negatively correlated. Overall, it is perceived that all factors, except RENT and EG, are positively correlated with REN usage.

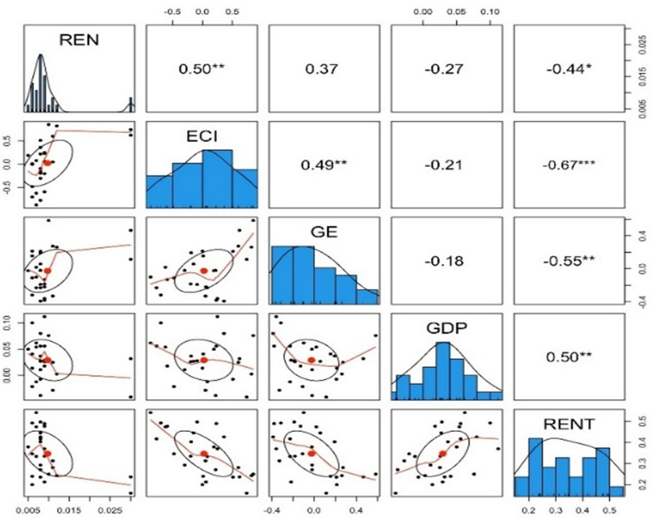


Fig. 1. Variables scatter plot.

The preliminary outcomes mentioned above suggest that these indicators drive REN usage in Saudi Arabia. However, these preliminary results must be considered with caution, as the correlation coefficients are estimated for the entire sample period and do not reflect the pattern of time and frequency variation of the correlation power. On the other hand, the Spearman correlation only indicates the strength of the linear connectedness among the selected variables. Thus, the non-linearity of dependence is vital to better understanding the relationships' intricacy. To this end, this study resorts to the WLMC to disentangle the drivers of REN usage.

B. The Wavelet Method

1) The Localized Multiple Regression

The local multiple regression theory serves as the basis of the WLMC. Let us consider X as a (n) multivariate time series dimension observed at time $t = 1, \ldots, T$. For $x_i \in X$, a local regression at a fixed $s \in \{t = 1, \ldots, T\}$ can be used to minimize the weighted sum of squared errors [36]:

$$S_s = \sum_t \theta(t-s)\left[f_s(X_{-i,t}) - x_{i,t}\right]^2 \qquad (1)$$

where $\theta(x)$ refers to a given moving average weight function depending on the time lag between X_t and X_s. $f_s(X_{-i})$ designates a local function of $\{X/x_i\}$ around s. If we let (s) vary over time, then the local coefficients of determination will be equal to:

$$R_s^2 = 1 - \frac{RwSS_s}{TwSS_s}(s) = 1, \ldots T \qquad (2)$$

$RwSS_s$ and $TwSS_s$ refer to the residual and the total weighted sum of squares, respectively.

2) The WLMC

Let us consider that $W_{jt} = (w_{1jt}, w_{2jt}, \ldots, w_{njt})$ are the wavelet coefficients for scale λ_j, with $j = \{1, 2, \ldots, J\}$ and J denotes the maximum level of the wavelet transform decomposition using the maximum overlap discrete wavelet transform to each of the used time series $x_i \in X$, $i = \{1, 2, \ldots, n\}$. The wavelet local and multiple correlations $\rho_{X,s}(\lambda_j)$, corresponding to a given scale λ_j can be estimated as the square roots of the regression coefficients of determination (2) for that linear combination of variables wij, $i = \{1, 2, \ldots, n\}$ [36]. where such determination maximizes coefficients. Subsequently, from (2) we get:

$$\hat{\rho}_{X;s}(\lambda_j) = \sqrt{R_{js}^2}\,;\ j = \{1, 2, \ldots, J\};\ s \in \{t = 1, \ldots, T\} \quad (3)$$

On the other hand, the coefficient of determination R^2 in the regression of z_i on the remaining variables of the system is equivalent to the square correlation between the observed and the generated $\hat{z}_i$ from such regression. A consistent estimator of the WLMC can be expressed [36]:

$$\hat{\rho}_{X;s}(\lambda_j) = Corr\left(\theta(t-s)^{\frac{1}{2}} w_{ij}, \theta(t-s)^{\frac{1}{2}} \hat{w}_{ij}\right), \quad (4)$$

$$s \in \{t = 1, \ldots, T\}$$

In (4), w_{ij} is chosen so that its multiple local regression on the regressors $\{w_{ij}, k \neq j\}$ maximizes the associated determination coefficients and $\hat{w}_{ij}$ designates the associated vector of fitted values of w_{ij} [11].

Methodically, three successive steps are followed, as observed in Figure 2, to carry out the WLMC analysis between GE, RENT, EG, EC and REN. First, this work proceeds to dataset visualization and statistic descriptions regarding stationarity, non-linearity, and normality. Second, it puts the WLMC method into operation. In doing so, bivariate, tri-variate, four-variate, and five-variate were explored. For each scenario, the WLMC heat maps were plotted and analyzed accordingly. Third, it checked the robustness of the WLMC results using the Granger spectral causality tests.

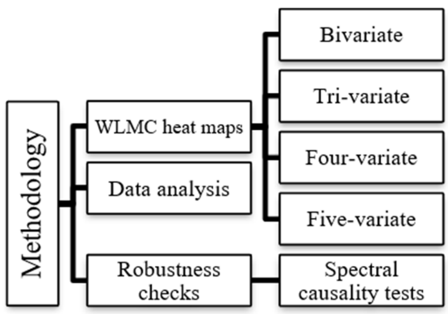


Fig. 2. Flow chart.

III. EMPIRICAL RESULTS AND DISCUSSIONS

A. The Bivariate WLMC Analysis

This study is concerned with the bivariate case (n = 2) and reports WLMC plots only for pairs that include REN. To make the WLMC interpretation straightforward, the bar color (right side) indicates the strength of the correlation with the red color referring to a strong positive correlation. In contrast, the blue one indicates a strong negative correlation. The periods are expressed in years and are reported on the left side. The white-colored intervals indicate that the correlation is insignificant at the 5% significance level. Figure 3a depicts the wavelet heat map for EC and REN. It indicates that their connectedness varies over time and frequencies. For instance, no significant correlation is found between the variables during the period 1997-2016 for [2-4] and [4-8] years' frequencies, whereas a strong and positive correlation is evidenced in the long run (above [4-8] years' frequencies). This outcome is expected due to the relative stability of the total REN in Saudi Arabia during this period. Another notable outcome from the WLMC heat map is the high positive correlation between EC and REN usage over the whole sample period when frequencies are higher than [2-4] year's frequency interval. This implies that EC is positively connected to REN and, therefore, can be perceived as a key factor that affects REN. A higher level of economic diversification results in a high use of REN [16]. However, this result is inconsistent with previous studies showing that economic diversification hinders the use of REN [18]. Another quite similar pattern is observed in Figure 3b, which depicts the WLMC heat map between GE and REN. No significant correlation is displayed during 1997-2016, whereas a strong and negative correlation appears during the sub-period 2016-2022.

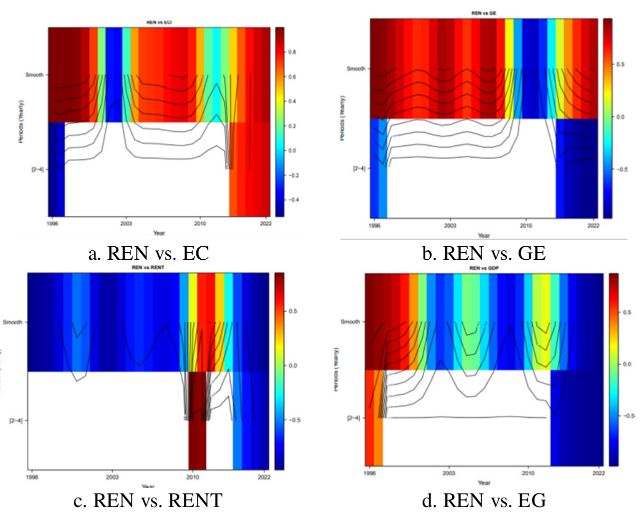


Fig. 3. WLMC heat-maps for the bivariate case. The wavelet filter was set as (wf) = "la8".

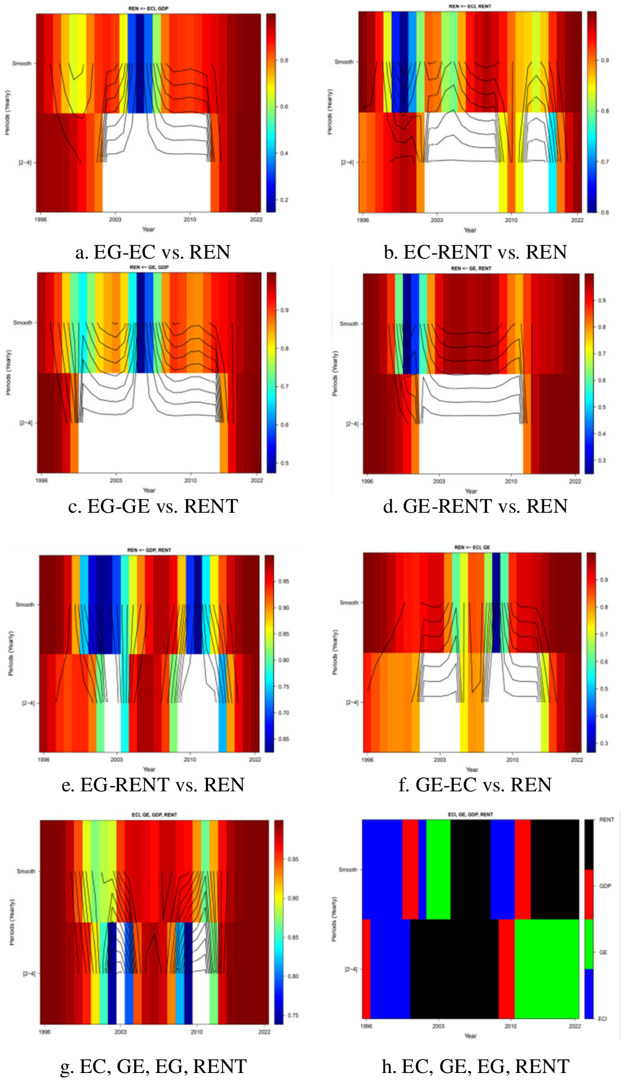
However, a strong positive correlation is visible in the [2-4] years frequency band. This implies that, in the long run, a higher GE will increase the use of REN in Saudi Arabia. The possible explanation for the strong correlation between 2016 and 2022 is that the Saudi government was bounded by the 2030 National Vision, implementing bold reforms to introduce REN, reduce total energy consumption and decrease energy intensity in the economy [37]. This outcome supports the argument that an effective government can enhance the use of cleaner energy by improving low-carbon production, incentivizing the production and usage of cleaner energy, and reducing the complexities inherent to the energy transition process [22]. Figures 3c and 3d report the heat maps for RENT-REN and EG-REN, respectively. The two heat map patterns are typically similar. They unveil a substantial negative correlation between the two variables and REN use over the whole sample period over the [2-4] years frequency. Again, no significant correlation is depicted during the sub-period 2017-2016, as indicated by the white-colored interval. This suggests that RENT and EG are negatively associated with REN in the long run. Regarding the effect of RENT on REN, our results are inconsistent with prior studies showing that RENTs are negatively correlated with REN in oil-rich exporting Middle East and North Africa (MENA) countries but are positively correlated in Golf Cooperation Countries (GCC) [30].

B. The Tri-Variate WLMC Analysis

In this section the tri-variate case is analyzed. Thus, the WLMC of the two selected variables is plotted against REN. Following [11], this study lets the WMLC select a variable instead of determining on (parameter ymaxr=NULL), which maximizes the multiple correlations for each wavelet scale. The main reason is that even though some of the selected time series are expected to be correlated, it is not revealed how these time series are interrelated through time scales and frequencies. In these WLMCs, the REN is chosen as the dependent variable. As it can be seen, the four heat map patterns are quite similar. All the interrelationships vary over time and frequencies. EG, EC, RENT and GE are heterogeneously correlated with REN. Figure 4a reports the WLMC plot between EG-EC and REN pairwise. As it can be observed, the white color interval indicates no significant correlation during the sub-period 2001-2012 for the frequencies of [0-2], [2,4], and [4-8] years. EG and EC have a positive joint effect on REN over the short and long run (i.e., all years' frequencies) for the remaining sub-periods. Figures 4b, 4c, and 4d reveal a very similar configuration. All the selected pair-wises are mostly positively and strongly correlated to REN. Figure 4g displays the WLMC heat map for all the selected variables. It can be noticed that all factors are strongly correlated throughout almost the entire sample period and for a shorter-longer period of fluctuation (except for years 2003, 2010, and 2012, there is no significant correlation) with time-varying correlation coefficients (0.75<CV<0.95). Given these strong connections between the variables in the time-frequency domain, it is more beneficial to identify the "dominant indicator" or the variable that augments the multiple correlations and can be used to describe the other indicators across periods and time intervals [11], [36]. As stressed earlier, the WLMC allows to identify the dominant variable. In other words, which variable among EC, RENT, GE, and GE is the most dominant in shaping the pattern of REN usage across frequencies and time intervals. Dominant variables are identified in Figure 4h. It demonstrates that RENT is more dominant than the others in explaining the multiple correlations, followed by EC and GE. This result can be explained by the fact that Saudi Arabia traditionally relied on oil as its main source of energy and income. This has led to less investment in REN sources. Furthermore, the government provides significant subsidies for oil production and consumption, making it more affordable than REN.

C. The Four-Variate Case

Figure 5 presents the WLMC heat map for the four variate cases. It highlights the joint effect of each of the three variables on the REN. The REN usage is chosen as the dependent variable. Figures 5a-5d display quite similar configurations; the joint effect of each of the three variables has a positive and significant effect on REN use.



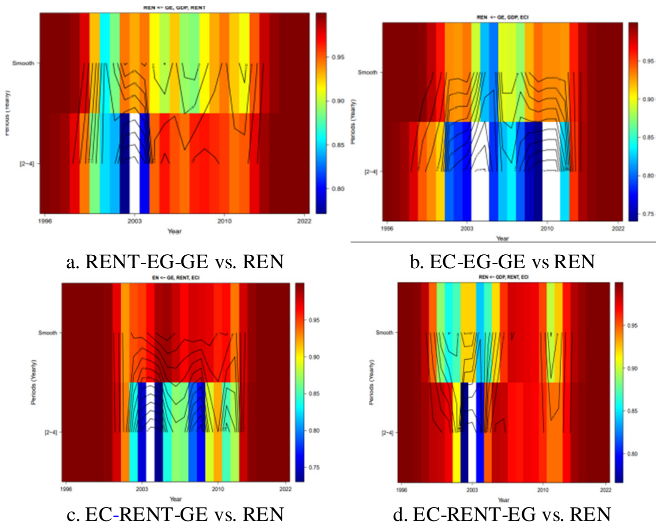
a. EG-EC vs. REN
b. EC-RENT vs. REN
c. EG-GE vs. RENT
d. GE-RENT vs. REN
e. EG-RENT vs. REN
f. GE-EC vs. REN
g. EC, GE, EG, RENT
h. EC, GE, EG, RENT

Fig. 4. WLMC heat maps: the tri-variate case.

The correlation coefficient ranges between 0.75 to 0.95. This positive connection is present throughout the sample period. This multivariate outcome is consistent with the WLCM analysis for the tri-variate case. From an economic perspective, this result suggests that in the long run, GE, RENT, and EC could be considered the key factors that shape the path of REN usage in Saudi Arabia.

IV. THE FIVE-VARIATE CASE

Figure 6 depicts the WLMC heat map plot for the five control variables to check their impact on the REN usage over time scales and frequencies. As it can be observed, the combined effect of the five variables is very strong, as indicated by the red color. The five variables are strongly and positively connected to REN usage. Compared to the four-variate scenario, the correlation is substantially higher (0.85<CV<0.95). This positive relationship spreads through the sample period and frequencies (short vs long). There is only one very short period in 2023 where the combined effect on REN is insignificant, as shown by the white-colored interval. This outcome is in line with the three and four-variate cases. EG, GE, RENT, and EC primarily drive the utilization of REN in Saudi Arabia. These factors strongly and positively affect the country's adoption and use of REN.



a. RENT-EG-GE vs. REN
b. EC-EG-GE vs REN
c. EC-RENT-GE vs. REN
d. EC-RENT-EG vs. REN

Fig. 5. WLMC heat maps: the four-variate case.

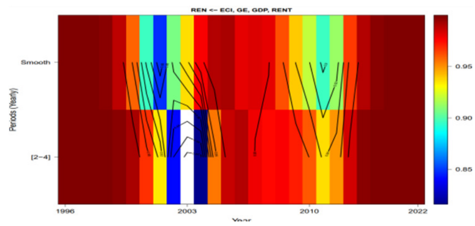
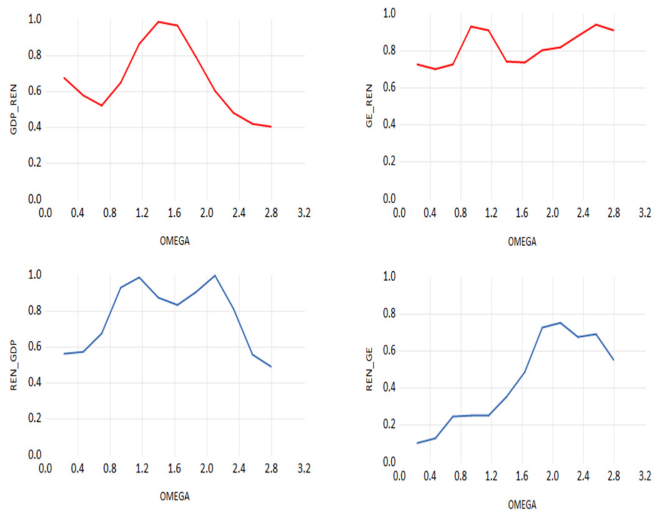


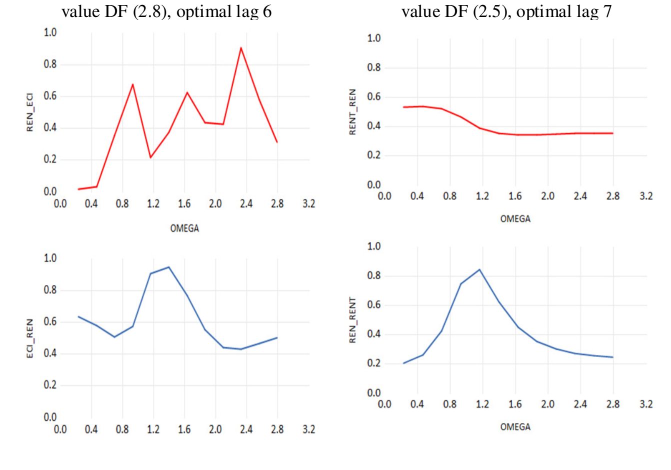
Fig. 6. The WLMC heat-map: the five-variate case.

A. The Robustness Checks: Spectral Granger Causality Tests

The spectral Granger causality test proposed by [38] was utilized to ensure the robustness of the WLMC outcomes. The aim was to examine the causality between GE, RENT, EC, EG, and the use of REN in the frequency domain. The results of the spectral causality test are plotted in Figure 7. This study tested the null hypothesis of no causality in the frequency omega against the alternative hypothesis. The optimal delay varies between tests and was specified using the Akaike information criteria. In Figure 7, the red line reflects probability values of the Granger causality running from each driver to REN use, varying across frequencies (from 0.4 to 3.2). As it can be noticed, the null hypothesis of a Granger causality absence for all the selected drivers (EG, GE, EC, and RENT) is rejected. For instance, GE is causing REN use for all the selected frequencies with probabilities ranging between 0.6 and 0.9. Similar results are obtained for the other control variables, except for EC, where the test probability is close to zero over the short-term (frequency lower than 0.4). This means that EC has no causal impact on REN usage in the short run, and its effect is mainly evidenced in the mid and long runs.



H_0: No causality at the frequency Omega, P. value DF (2.8), optimal lag 6 H_0: No causality at the frequency Omega, P. value DF (2.5), optimal lag 7



H_0: No causality at the frequency Omega, P. value (DF): 2.5, optimal lag 7 H_0: No causality at the frequency Omega, P. value (DF): 2.5, optimal lag 7

Fig. 7. The spectral causality tests.

The results of the Granger causality test support the findings of the WLMC in the sense that they confirm that EC, EG, GE, and RENT are key drivers of the REN use in Saudi Arabia and that their causal links vary substantially over frequencies. The WLMC scenarios have demonstrated a strong correlation between REN and all selected control variables despite the varying time-scale pattern of the drivers-REN nexus. Moreover, the Granger spectral causality results have further supported the outcomes of the WLMC. These findings bear significant implications for the future of renewable energy usage and its control variables. The WLMC scenarios have demonstrated a strong correlation between REN usage and all selected control variables despite the varying time-scale pattern of the drivers-REN nexus. Moreover, the Granger spectral causality results have further supported the outcomes of the WLMC. These findings bear significant implications for the future of renewable energy usage and its control variables.

V. CONCLUSIONS

In this paper, the relationship between government effectiveness, economic growth, economic complexity, oil rents, and the use of renewable energy in Saudi Arabia from 1996 to 2022 was studied. The novel method of Wavelet Local Multiple Correlation regression (WLMC), which considers non-stationarity and non-linearity when investigating the correlations across different time scales and frequencies, was employed. This study makes a unique contribution in three different ways: It introduces the WLMC method, which examines the differential and combined effects of various control variables on renewable energy use in the time-frequency domain. This work differs from previous research by considering several macroeconomic indicators and institutional factors to assess their impact on the development of renewable energy use. Also, this work identifies the key determinants among the selected drivers. This research provides valuable insights to the renewable energy literature by proposing a useful tool to better understand how macroeconomic and institutional factors can enhance or impede the development of renewable energy in heavy oil-dependent economies, such as Saudi Arabia. By clarifying these complexities, appropriate strategies and energy policies can be designed to promote renewable energy use within the UN Sustainable Development Goals.

The WLMC analysis revealed that, despite the time-frequency varying pattern of their interrelationships, oil rents, economic growth, government effectiveness, economic complexity, and renewable energy usage are significantly and positively interconnected in the long run. Although their short-term correlations are substantially lower and turned out to be insignificant for some small-time intervals. According to the outcomes, oil rents and government effectiveness are the most influential factors. The findings' robustness was tested by implementing the Granger Spectral Causality approach to determine the extent to which the selected control variables influence the use of renewable energy over time scales. The results clearly support the WLMC analysis, demonstrating that government effectiveness, economic growth, economic complexity, and oil rents significantly affect renewable energy use. These factors have a substantially more relevant impact in the long run. The research findings of the study offer significant policy implications for promoting the use of renewable energy in Saudi Arabia. Policymakers should encourage the production of green energy while penalizing the use of fossil-based resources. They should prioritize promoting cleaner energy production, reducing the complexities that impede the green energy transition process, and adopting financial incentives policies. Further research is recommended, including a comparative analysis of other oil-rich countries in the Golf Cooperation Countries (GCC), and exploring other factors that influence renewable energy development.

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APPENDIX

BRIEF LITERATURE REVIEW

Ref.	Data sample	Methods	Main conclusions
Panel A: Economic Complexity and Renewable Energy			
[15]	18 countries (1995-2017)	QR	R&D increases the consumption of REN and economic complexity decreases it.
[16]	G7 and E-7 countries	Panel	EC affects REN energy.
[17]	29 Asia-Pacific countries	Panel	An increase in REN use reduces carbon emissions in countries with lower EC levels.
[18]	94 countries	PQR	EC impedes both energy efficiency and REN use.
[39]	G7 countries (1980-2017)	PQR	EC hampers the development of REN.
Panel B: Government Effectiveness and Renewable Energy			
[40]	60 countries (2007-2017)	GMM	GE supports renewable energy policies.
[1]	9 MENA countries, (1984-2014)	PQR	The interaction term between GE and financial development is harmful for the lower quantiles but positive for the highest quantiles. Political stability, GE, and financial development are key drivers of REN use.
[41]	MENA countries (1984-2014)	PSTR	Governance effectiveness, innovation, political stability, and financial development are the key drivers of REN energy development deployment.
Panel C: Economic growth - Oil rents - Renewable Energy			
[23]	China (1990-2020)	QARDL	RENTs, financial development, and EG influence carbon emissions and impact REN energy.
[24]	China, data (1971-2018)	ARDL	A long-run relationship is evidenced between REN, EG, greenhouse emissions, and RENT.
[25]	China and USA, (1900-2015)	ARDL	Long-run relationship among gas/oil/coal rents, REN and non-REN energy, and EG.
[42]	BRICS (1990-2020)	PQR	A bidirectional causality between carbon emissions and economic performance, RENT and EG.
[30]	8 MENA countries (1996-2020)	DOLS	Oil rents are negatively associated to REN in MENA oil-exporters but positively correlated in GCC countries.
[23]	E-7 economies	MMQR	Sustainable management of RENTs permits diversification from carbon-intensive sectors.
[28]	44 countries	Panel	RENT positively affect renewable energy use, and investment taxes directly affect REN.
[21]	Global data (1988-2021)	FMOLS	RENTS have a positive effect on renewable energy consumption.
[43]	Saudi Arabia (1990-2019).	ARDL,	REN energy and total natural resources rent reduce the material footprint.
[44]	BRICS (2016-2023)	NARDL	The use of REN results in higher economic growth and lower environmental degradation.

Notes: EG: economic growth; REN: renewable energy; GE: government effectiveness; EC: economic complexity; ECI: economic complexity index; FMLOS: fully modified ordinary least squares; DOLS: dynamic ordinary least squares; CS-ARDL: cross-sectional autoregressive distributed lags; QR: quintile regression; PQR: panel quintile regression, PSTM: Panel Smooth Transition Model; MMQR: method of Moment quintile regression; QARDL: quantile autoregressive distributed lagged approach; ECM: Error Correction Model; ARDL: autoregressive distributed lag model; NARDL: nonlinear autoregressive distributed lag model; QARLD: quintile ARDL model; GMM: generalized methods of moments.

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