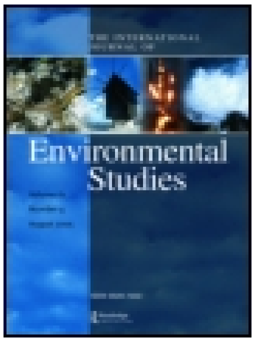

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ARTICLE

Examining the linkages among electricity consumption, income and environmental pollution in Saudi Arabia: from a spectral wavelet analysis to the Granger Causality test

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ABSTRACT
This study investigates the relationship among electricity consumption, per capita GDP, and CO_2 emissions for the Kingdom of Saudi Arabia. Trade openness and urbanisation are included within a multivariate approach. Using data covering the 1971–2018 period, the wavelet-coherence analysis is applied to assess the interactions amongst variables. All variables except trade openness appear highly correlated with CO_2 emissions. This is further confirmed by our causality testing procedure (i.e. the Johansen and Juselius test for cointegration and the Granger Causality test applied on a Vector Auto-Regressive model) which shows that electricity consumption, per capita income and urbanisation are crucial determinants of CO_2 emissions. Accordingly, adequate policy measures are proposed to turn the Saudi power sector towards a sustainable path.

KEYWORDS
CO_2 emissions; electricity consumption; wavelet analysis

Introduction

There is worldwide concern that environmental pollution poses serious threats to natural resources and health. Countries face pressure to turn towards a sustainable path, for the benefit of mankind as a whole. In 2013 the Intergovernmental Panel on Climate Change stated that '*greenhouse gases related to human activities are the most significant driver of observed climate change since the mid-20th century*'. Indeed, the emissions from Greenhouse Gas (GHG) are responsible for raising the average temperature on the earth, with carbon dioxide (CO_2) being the most harmful and pollutant[1] [1]. A well-known intellectual tool is named the Environmental Kuznets curve (EKC) hypothesis. First introduced by Grossman and Krueger [2], it postulates that environmental degradation and pollution increase during the early stage of economic development. As income grows, it reaches a turning point after which environmental pressure reduces and environmental quality ameliorates. In that case only, an inverted U-shaped curve emerges among variables. Hence, it can be argued that economic growth itself is the solution for environmental concern mitigation [3].

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The Kingdom of Saudi Arabia (KSA) is a relevant focus in this discussion both because of the character of its economy and the issue of energy and fossil fuels. KSA is the largest oil producer worldwide and its economy is highly dependent on fossil fuel export. This latter element is one of the main determinants of climate change and pollution. Some key figures must be mentioned. First, the country displays significant proven reserve of oil: 297.6 billion barrels, more than 18% of global reserves [4]. Second, the oil industry sector accounts for 70% and 50% of export revenues and GDP, respectively. Additionally, the country is heavily based on fossil fuel consumption. Particularly, KSA over the last decades has witnessed a rapid growth of demand for the oil and its derivatives as well as gas and liquid gas. For instance, the country has experienced a significant increase in the consumption of oil from (389 thousand barrel/day) in 1965 to (3.787 million barrel/day) in 2019 [4]. Third, KSA is nowadays the sixth largest oil consumer in the world (after USA, China, India, Japan, and Russia), and its domestic consumption currently account for more than 25% of the national oil production.

Undoubtedly, the oil industry is at the centre of several economic and export opportunities crucial to KSA's development [5]. According to Fattouh and El-Katiri [6], the elevated domestic consumption of oil in KSA finds multiple explanations. Upon them, the subsidising of oil prices that has been carried by the government for a long time, the booming population growth, and the recent rapid industrial and economic development have strongly influenced the national demand for energy. An important amount of polluting particles is released into the atmosphere by the combustion of fossil fuels to generate power. Being highly dependent on non-renewable sources, the electricity sector in KSA still generated 76.2% of its electricity from oil, natural gas, and coal in 2015 [7]. The exponential growth of the energy (and especially power) demand observed these past decades is notable. According to the IEA [8], the total consumption of electricity has increased from 165.7 ktoe to 26 497.4 ktoe over the period 1971–2018. As a result, carbon emission trends have recorded critical levels with concern for the future.[2] The sustainability of the region is questionable. Polluting particles induce harmful environmental [9–11] and health effects [12–14] but also adverse socio-economic consequences [15–17].

Recently, KSA's policymakers have become concerned at the nature of the country's energy patterns, affecting the climate but being the core of solutions [18]. With a significant potential for renewable energy generation,[3] KSA has installed solar PV capacity notably, although there is much scope for more improvements [19,20]. In addition, the ways energy is consumed have also been the subject of recent policies. For instance, an energy efficiency plan aims at limiting the growth of power needs at 14% by 2021, while preparing the energy sector to the transition towards a more diversified economy[4] [21]. Before implementing adequate policies, further inquiry should be made into the carbon emission determinants in KSA. As a matter of fact, if electricity generation and income are identified as the main drivers of environmental pollution, then appropriate conservation, efficiency, and low-carbon policies could be implemented. Inversely, if other macroeconomic indicators are found to boost the emissions of CO_2 in KSA, they should be incorporated into future environmental planning. Therefore, knowing the direction and the magnitude of the relationship among CO_2 emissions and various potential drivers can be crucial for KSA's policymaking.

Figure 1 presents the time plots of CO_2 emissions (variable *CO2* – measured on the right axis in thousand tons) and electricity power consumption (variable *EPC* – measured

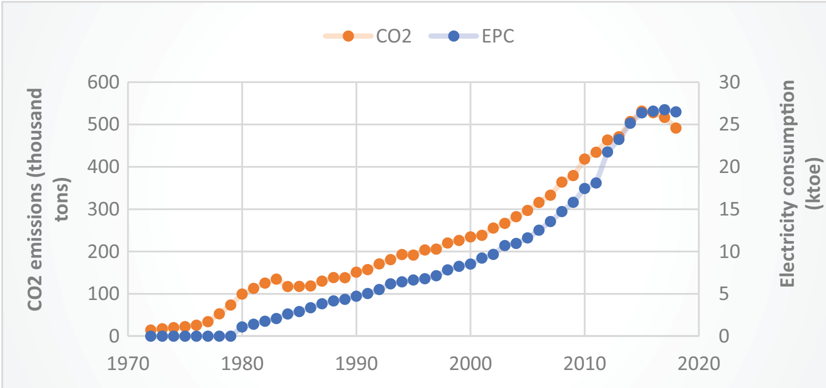

Figure 1. Electricity consumption and CO_2 emissions in KSA, 1971–2018.
Source: Our elaborations based on IEA [22,23] data.

on the left axis in kilotons of oil equivalent (ktoe)) for the period 1971–2018. Data were obtained from the International Energy Agency (IEA) Statistics [22,23]. The figure indicates evidence of a strong and positive correlation between the series, especially for the last decade. One observes that electricity power consumption displays a constant expansion over time in KSA. Similarly, the growth of CO_2 emissions presents only a few variations over time, especially in the last couple of years where a possible coupling phenomenon among the series tends to occur. Hence, there is a point in investigating the polluting effect of the power generation in KSA since this sector seems to concentrate key climate issues but also non-negligible solutions.

Another striking determinant must be tackled. Being the main feature of globalisation, trade openness is thought to be a non-negligible driver of environmental pollution, although its direct role in climate change remains controversial [24]. On the one hand, fuel combustion for trade purposes releases harmful emissions into the atmosphere and such externalities are a positive function of trade flows. On the other hand, international trade may play a crucial role in the decarbonisation of the energy sector as it facilitates the technology transfer for renewable energy products across countries (including exports of raw materials and components but also renewable natural sources to produce energy) [25,26]. The nature of the trade–environment relationship depends on scale, technique, and composition effects [27]. Undoubtedly, the KSA trend in CO_2 emissions may display a serious sensitivity to changes in trade openness, as the foreign exports of primary energy have become a dominant share of GDP. Therefore, it must be incorporated within our framework.

Karanfil and Li [28] examined 160 countries divided into 13 subsamples and found that the electricity–growth relationship is very sensitive to the level of urbanisation; which may exert substantial pressure on environmental quality [29,30]. Since KSA has rapidly urbanised over the past few decades, we include this factor within our energy-GDP-emissions framework, as our predicted causalities can be potentially undermined otherwise. The environmental issue facing KSA is how to answer the growing sectoral energy demands in more secure and less costly energy procurement, and, at the same time, how to reduce carbon emissions associated with the economic activity [31].

This paper brings two novelty features to the literature. First, this is the first empirical assessment on the linkages among power electricity use, economic growth, CO_2 emissions, urbanisation, and trade openness for KSA. Second, the research employs an innovative estimation strategy never used on these linkages before: the Wavelet Coherence Analysis (WCA). This presents multiple advantages. Initiated by Ramsey and Lampart [32], this strategy can determine patterns of behaviour for different time horizons by testing the causality of each time scale with the pertinent ones of the other series [33,34]. Only a few empirical energy-growth-pollution nexus studies have been conducted with this methodology,[5] calling for further inquiry into the KSA case.

Accordingly, the present study examines the relationship among CO_2 emissions, economic growth, electricity consumption, trade openness, and urbanisation in the case of KSA. To do so, a Wavelet Coherence Analysis (WCA) is employed using data spanning the 1971–2018 period. Then, to give evidence of causal inferences among variables, a stationary (the Augmented Dicky and Fuller (ADF) test; the Phillips and Perron (PP) test) and cointegration (the Johansen and Juselius cointegration test) procedures are followed by the Granger Causality test (GC), applied on a Vector Auto-Regressive (VAR) model. Empirical results are thought to bring high information value for policy purposes in KSA.

Besides the Introduction, Section 2 presents the relevant literature and underlines the key gaps within. Section 3 displays the theoretical framework relative to the wavelet analysis. Section 4 outlines the results and provides a discussion. Section 5 gives concluding remarks and suggests policy implications.

Literature survey

A prominent literature has focused on the relationship among economic growth, energy consumption, and environmental degradation. Using various time-series methodologies, this nexus has been extensively studied. Regarding KSA, this economy has been mostly included within large and heterogeneous samples of countries. On the other hand, only a few single-country assessments have been performed on that case, but they display conflicting findings. Often avoided, the electricity use determinant has been overlooked by the literature and calls for further inquiry. Our review stands in two parts: the multi-country investigations including the KSA *(2.1.)*, and the single-country assessments on this case *(2.2.)*. Lastly, the main gaps in the literature are highlighted and a research proposal is formulated.

Multi-country studies on the relationship among energy consumption, CO_2 emissions, and GDP including KSA

Regarding the first strand of the literature, a range of panel assessments have been conducted on the relationship among energy consumption, economic growth and environmental pollution. These include Al-Mulali [35] for different economic regions; Saboori et al. [36] for OECD economies; Cowan et al. [37] for BRICS countries; Linh and Lin [38] for Asian countries; Destek and Aslan [39] for G-7 countries. In recent years, interest in GCC counties has increased. The aim of this review is to outline the relevant related literature. Research works are ordered as follows: growth, conservation, feedback, and neutral hypothesis.

Above all, the literature has displayed weak support to the 'growth hypothesis' as most of the papers did not find evidence of a unidirectional link from energy consumption to economic growth. Nonetheless, through a causality analysis in the frequency domain, Gorus and Aydin [40] showed that energy consumption Granger causes output growth but also CO_2 emissions in the MENA region.

The 'conservation hypothesis' has been abundantly validated. First, Farhani et al. [41] assessed the causal relationship among energy use, GDP and carbon emissions for a sample of 11 MENA economies (including Bahrain, Oman, and KSA) over the period 1980–2009. Vector Error Correction Model (VECM)'s results showed that GDP growth causes energy use for the whole sample but not *vice versa*. Besides, time-series results established that energy consumption and GDP are both strong drivers of CO_2 emissions. This is in line with Ozcan's findings [42], a study extending this analysis to 12 MENA countries (including Oman, Bahrain, the UAE and KSA). Using short and long-run causality tests (i.e. Engle and Granger [43]) over the period 1990–2008, Ozcan validated the 'conservation hypothesis'. Finally, although the UAE, Oman and Bahrain revealed an inverted U-shaped curve (EKC) between output growth and carbon emissions, no evidence of such relationship was provided for KSA.

Salahuddin and Gow [44] applied panel Granger Causality (GC) techniques over the period 1980–2012 for GCC countries. A one-way causality was underlined from growth to energy use, but a feedback channel was found with regard to the energy–CO_2 relationship. Following that, Asif et al. [45] employed the Fully Modified Ordinary Least Square (FMOLS) and Dynamic Ordinary Least Square (DOLS) estimations for GCC countries using data from 1980 to 2011. Their findings established a positive association between urbanisation, growth, and energy use and carbon emissions for the whole sample. In addition, the linear panel estimation method based on the modelling of Dumitrescu and Hurlin [46] provided evidence of a one-way causality from GDP to the consumption of energy in KSA and Bahrain, which is congruent with the 'conservation hypothesis'.

Similarly, Magazzino [47] performed an empirical examination on the energy use-economic growth-CO_2 emissions nexus for 10 MENA economies. With data spanning the 1971–2006 period, the Panel Vector Auto-regressive (VAR) model showed a negative response of GDP to shock in CO_2 for the six GCC countries. This was confirmed by the Impulse Response Function (IRF). Furthermore, findings reflected the central role played by economic growth on the trends of energy use and CO_2 emissions. Looking at the same sample, Bekhet et al. [48] inspected the linkages among energy consumption, financial development and economic growth and relied on Autoregressive Distributed Lag bounds (ARDL) and VECM from 1980 to 2011. Evidence of a long-run causality from CO_2 emissions, financial development, and GDP to energy use was found, in line with the 'conservation hypothesis' for the whole sample, except the UAE. Overall, carbon emissions are found to cause energy consumption for KSA, Qatar, and the UAE, but not *vice versa*.

By contrast, the 'feedback hypothesis' has been confirmed in Omri [49] while exploring the causal link between energy use, GDP and carbon emissions for 14 MENA countries (including Bahrain, Kuwait, Qatar, the UAE, KSA, but also Oman) from 1990 to 2011. Applying the Generalised Method of Moments (GMM) on a Cobb-Douglas production function, empirical results highlighted the existence of a bidirectional causality among energy use and output growth. Besides, a unidirectional link from energy consumption to carbon dioxide emissions was found. All in all, Magazzino [50] tested the causal linkages for GCC countries with data spanning the 1960–2013 period. GC results showed evidence of the 'growth hypothesis' in Oman, Qatar, and Kuwait, but a feedback mechanism is established for KSA. This indicates that the consumption of energy improves growth and *vice versa* in this latter economy. Such results confirm the preliminary evidence found by Al-Mulali [35] for 17 MENA countries.

A very few 'neutral hypotheses' have been confirmed by the literature. Sari and Soytas [51] examined whether environmental and economic targets are compatible over the long run for 5 OPEC countries (including KSA). These researchers examined the relationship among income, energy consumption, total employment, and carbon emissions. ARDL's findings displayed evidence of a cointegrating relationship only for KSA. Moreover, Sari and Soytas [51] rejected the existence of any significant causality among variables for the whole sample, concluding that '*none of the countries need to sacrifice economic growth to decrease their emission levels*' [51]. In the end, Hamdi and Sbia [52] found the same results while focusing on GCC over the period 1980–2009. The existence of an inverted-U-shaped curve has been highlighted for the six economies, which is in line with the conclusions of Arouri et al. [53] for 12 MENA countries.

Tightly linked to this view, Magazzino and Cerulli [30] incorporated per capita carbon emissions, GDP, urban population, trade, and per capita energy use data related to 17 MENA countries (period 1971–2013) in a single framework. Using a Responsiveness Scores (RS) approach, they showed that energy use responds positively to shock in per capita GDP and *vice versa*. But trade and urban population showed negative responses, with mild increasing returns to scale. Lastly, Zmami and Ben-Salha [54] performed an empirical analysis on the determinants of CO_2 emissions in GCC countries with data from 1980 to 2017. Using the Stochastic Impacts by Regression on Population, Affluence, and Technology (STIRPAT) model, the authors established that energy consumption and Foreign Direct Investment (FDI) are associated with more polluting emissions in the long run; urbanisation displays a mitigating effect on environmental degradation. Finally, results supported the validity of the EKC for the whole sample, with an income threshold level estimated at US$56,350.928. An extensive review on the energy-GDP literature on GCC countries can be found in Magazzino and Cerulli [30]. Table 1 summarises the key information on this above-mentioned literature.

Single-country assessments on KSA

While KSA has been often included within panel analyses, the literature lacks single-country assessments on that case. To the best of our knowledge, seven seminal papers have addressed this issue so far [55–61] although their methodologies and variables selected differ.

Alkhathlan et al. [55] applied the Autoregressive Distributed Lag (ARDL) model and the Vector Error Correction Model (VECM) on GDP, CO_2 emissions, energy consumption and employment ratio data in KSA. Focusing on the 1980–2008 period, their results indicated that neither energy consumption per capita nor carbon emissions per capita improve GDP per capita, while employment ratio causes GDP per capita in the short run.

Table 1. Summary of previous studies on energy consumption, CO_2 emissions, and GDP for GCC countries.

Author(s)	Countries	Period	Methodology	Variables	Causality
Sari and Soytas [51]	5 OPEC countries	1971–2002	ARDL	Energy consumption, GDP, and CO_2 emissions, employment	E Y and Y C
Al-Mulali [35]	17 MENA countries	1980–2009	ECM, GC	Oil consumption, GDP, and CO_2 emissions,	OC↔Y, OC↔C and Y↔C
Arouri et al. [53]	12 MENA countries	1981–2005	CCE model	Per capita energy consumption, per capita GDP, per capita CO_2 emissions	E→Y and Y→C
Farhani et al. [41]	11 MENA countries	1980–2009	VECM	Energy consumption, GDP, and CO_2 emissions	Y→E and E, Y→C
Omri [49]	14 MENA countries	1990–2011	GMM	Energy consumption, GDP, and CO_2 emissions	E↔Y and E→C
Ozcan [42]	12 MENA countries	1990–2008	VECM	Energy consumption, GDP, and CO_2 emissions	Y→E
Hamdi and Sbia [52]	GCC countries	1980–2009	VECM	Energy consumption, GDP, and CO_2 emissions	E Y
Salahuddin and Gow [44]	GCC countries	1980–2012	GC	Energy consumption, GDP, and CO_2 emissions	Y→E
Asif et al. [45]	GCC countries	1980–2011	FMOLS, DOLS, DHC	Energy consumption, GDP, and CO_2 emissions, urbanisation	E, Y, U→C E↔Y (Oman and the UAE) and Y→E (KSA and Bahrain
Magazzino [47]	10 MENA countries	1971–2006	VAR, IRF	Energy consumption, GDP, and CO_2 emissions	Y→E, C
Magazzino [49]	6 GCC countries	1960–2013	GC	Energy consumption, GDP, and CO_2 emissions	E→Y (Kuwait, Oman, and Qatar) and E↔Y (KSA)
Bekhet et al. [48]	GCC countries	1980–2011	ARDL, VECM	Energy consumption, GDP, and CO_2 emissions, financial development	Y→E (except the UAE) and C→E (KSA, the UAE, and Qatar)
Gorus and Aydin [40]	8 MENA countries	1975–2014	GC in the frequency domain	Energy consumption, GDP, and CO_2 emissions	E→Y, C
Magazzino and Cerulli [30]	17 MENA countries	1971–2013	RS approach	Energy consumption per capita, GDP, CO_2 emissions per capita, urban population, and trade	-
Zmami and Ben-Salha [54]	GCC countries	1980–2017	STIRPAT model	Energy consumption, GDP, CO_2 emissions, urbanisation, foreign direct investments, trade	E→C FDI→C

Source: Our elaborations.

Notes: OC, Y, E, C, U and FDI represent oil consumption, economic growth, energy consumption, CO_2 emissions urbanisation, and foreign direct investments, respectively. A ⟶ B indicates the existence of a unidirectional causality from A to B. A ↔ B indicates the existence of a bidirectional causality between A and B. A □ B refers to the absence of causality between A and B. ARDL: Auto Regressive Distributed Lag bounds; CCE model: Common Correlated Effects model; DHC: Dumitrescu and Hurlin Causality; DOLS: Dynamic Ordinary Least Squares; GC: Granger Causality; FMOLS: Fully Modified Ordinary Least Squares; GMM: generalised Method of Moments; IRF: Impulse Response Function; RS: Responsiveness Scores; STIRPAT model: Stochastic Impacts by Regression on Population, Affluence, and Technology model; VAR: Vector Auto-Regressive; VECM: Vector Error Correction Model.

Extending the previous analysis, Alkhathlan and Javid [56] confirmed the 'growth hypothesis' in examining the relationship among economic growth, per capita carbon emissions and per capita energy use for KSA. Using Granger causality (GC, Granger [62]) test over the period 1980–2011, dynamic causality results indicated that the consumption of energy drives growth in KSA over the long period. Furthermore, they established that increase in per capita carbon emissions is mostly caused by per capita income rise in this country, rejecting the Environmental Kuznets Curve (EKC) hypothesis. This corroborates Alshehry and Belloumi's [57] findings since the authors found evidence of a long-run unidirectional causality from per capita energy consumption to per capita economic growth and per capita CO_2 emissions using VECM, Granger Causality (GC) and Impulse Response Function (IRF) from 1971 to 2010. Raggad [58] assessed the existence of a long-run relationship between CO_2 emissions, economic growth, energy use, and urbanisation in KSA over the 1971–2014 period. ARDL results established that energy use and economic growth increase pollution, while urbanisation decreases pollution. Recently, Toumi and Toumi [59] applied non-linear ARDL model over the period 1990–2014 and concluded that negative shocks in CO_2 emissions display only positive impacts on real GDP in the long-run. Besides, the asymmetric causal relationship from CO_2 emissions to renewable energy consumption is neutral in the long term, but positive shocks to renewable energy induce CO_2 emission reduction in the long term. All in all, Algarini [60] extended the standard energy-GDP- CO_2 framework by including data on energy production from oil and gas. While the authors performed a causality analysis using GC on a Vector-Autoregressive (VAR) model from 1990 to 2017, results provided evidence of a unidirectional link from energy consumption and CO_2 emissions, to growth of electricity production from gas. Similarly, a one-way causality was found from energy production from oil to CO_2 emissions, indicating that energy production should be considered as a complementary production factors to labour and capital, since it plays a central role in the production process in KSA. Overall, Raggad [61] employed non-linear ARDL coupled with the asymmetric causality test of Hatemi-J [63] among economic growth, energy use, and financial development, on CO_2 emissions in KSA, from 1971 to 2014. Related findings concluded that economic growth causes CO_2 emissions and CO_2 emissions cause energy consumption, while no causal link is established between financial development and environmental pollution. Table 2 outlines the main findings on this empirical literature.

Although it is non-exhaustive, this literature review underlines three important points. First, the KSA case has been mostly analysed as part of large and heterogeneous panel assessments. Results often conflict without enabling country-specific policy implications. Besides, we found that most papers excluded urbanisation and trade openness from their analysis, although they may be non-negligible drivers of environmental pollution. Being exceptional for its economic and energy characteristics, KSA has been the subject of a few single-country assessments; but all of them relied on aggregate energy data, avoiding any finer analysis on the electricity source. In addition, related studies only relied on time-series cointegration and causality tests (mostly ARDL, VECM, GC) with no clear consensus regarding the results. Further inquiries into the energy-GDP-pollution nexus using the most advanced empirical tools are necessary.

Accordingly, this paper employs a Wavelet Coherence Analysis (WCA) to investigate the linkages among electricity consumption, economic growth, CO_2 emissions, trade

Table 2. Summary of previous single-assessments on the Kingdom of Saudi Arabia (KSA).

Author(s)	Countries	Period	Methodology	Variables	Causality
Alkhathlan et al. [55]	Saudi Arabia	1980–2008	ARDL, VECM	Energy consumption per capita, GDP per capita, CO_2 emissions per capita, and employment ratio.	ER→Y, E⇎Y and C⇎Y
Alkhathlan and Javid [56]	Saudi Arabia	1980–2011	GC	GDP, CO_2 emissions per capita and energy consumption per capita	E→Y and Y→C
Alshehry and Belloumi [57]	Saudi Arabia	1971–2010	VECM, GC, IRF	Energy consumption per capita, GDP per capita, CO_2 emissions per capita and energy price.	E→Y, C and Y⇎;C
Raggad [58]	Saudi Arabia	1971–2014	ARDL	Energy consumption, GDP, CO_2 emissions, urbanisation.	E, Y→C and
Toumi and Toumi [59]	Saudi Arabia	1990–2014	NARDL	Renewable energy consumption, GDP, CO_2 emissions.	-
Algarini [60]	Saudi Arabia	1990–2017	VAR, GC	Energy consumption, GDP, CO_2 emissions and and energy (including electricity) production from oil and gas.	E, C→ELPG and EPO→C
Raggad [61]	Saudi Arabia	1971–2014	NARDL, H-J	Energy consumption, GDP, CO_2 emissions, financial development.	Y→C, C→E and FD⇎;C.

Source: Our elaborations.

Notes: ER, Y, E, C, ELPG, EPO, and FD represent employment ratio, economic growth, energy consumption, CO_2 emissions, electricity production from gas, energy production from oil, and financial development, respectively. A → B indicates the existence of a unidirectional causality from A to B. A ↔ B indicates the existence of a bidirectional causality between A and B. A⇎ B refers to the absence of causality between A and B. "-" indicates that assessing the nature of the energy-GDP hypothesis is not the explicit aim of the paper. ARDL: Auto Regressive Distributed Lag bounds; GC: Granger Causality; H-J: Hatemi-J [61] asymmetric causality test; IRF: Impulse Response Function; NARDL: non-linear Auto Regressive Distributed Lag bounds; VAR: Vector Auto-Regressive; VECM: Vector Error Correction Model.

openness, and urbanisation in the case of KSA. This innovative approach has never been adopted to inspect this singular case before. Then, to give evidence of causal inferences among variables, stationary (the Augmented Dicky and Fuller (ADF) test; the Phillips and Perron (PP) test) and cointegration (the Johansen and Juselius cointegration test) procedures are followed by the Granger Causality test (GC), applied on a Vector Auto-Regressive (VAR) model. Data cover the most recent and available period: 1971–2018. Empirical results might bring useful information to environmental planners in KSA.

Data and methodology

Data collection and functional form

The current study aims to examine the effect of electric power consumption, economic growth, urbanisation and trade openness on the emission of CO_2 in the largest oil producer and exporter country, KSA. A time series dataset has been employed and covers the 1971–2018 period for all variables. The data were collected from various sources: the World Bank Development Indicators database[6] [7], the IEA World Energy Statistics and Balances[7] [22], and the IEA CO_2 Emissions from Fuel Combustion Statistics[8] [23]. No missing value was reported. Table 3 summarises the main information on the variables.

The following functional form for the study case was proposed:

$$CO_2 = f(GDP_t, EPC_t, TO_t, UR_t) \quad (1)$$

CO_2 refers to carbon dioxide emissions from fuel combustion (in thousand tons), *GDP* is the real per capita GDP (in constant 2010 US$), *EPC* is the electric power consumption (in kilo tons of oil equivalent – ktoe). *TO* indicates trade openness (summation of percentage of imports and exports to GDP), as proposed by Hossain [64] and Akın [65]; *UR* represents the urbanisation (the share of urban population in total population) *t* represents the time period.

Theoretical wavelet framework

To investigate the time-frequency dependence of *CO2* and *EPC, GDP, TO*, and *UR* in KSA, the study used the wavelet coherence technique. With a wavelet analysis, a time-series could be separated into frequency elements. Although the Fourier analysis has a full ability of representation and decomposition of stationary time-series, the research could be conducted with a nonstationary time-series through wavelets. Furthermore, wavelets promote the conservation of time for localised information, enabling co-movement to be measured in the time-frequency space.

Wavelet Coherence analysis is mainly time series analysis. The cross wavelet transform is defined by two stock index time series *x(t)* and *y(t)* with the continuous transforms of *wx(u,s)* and *wy(u,s)*. Where, u is the position index, s is the scale, * refer to the complex conjugate. Finally, to test the coherence of the cross wavelet transform in the time frequency space, and following Torrence and Webster [66] and Grinsted et al. [67], we apply the wavelet squared coherence called wavelet coherence that can be defined as:

Table 3. Data information.

Variable	Definition	Data period	Source
Trade openness (TO)	Summation of percentage of imports and exports to GDP	1971–2018	World Development Indicators [7]
Electricity consumption (*EPC*)	Total electricity consumption in kilo tons of oil equivalent (ktoe)	1971–2018	IEA World Energy Statistics and Balances database [22]
Economic growth *(GDP)*	Per capita GDP in Constant 2010US$	1971–2018	World Development Indicators [7]
Urban population (*UR*)	Urban population in % of the total population	1971–2018	World Development Indicators [7]
CO_2 emissions (*CO2*)	CO_2 emissions from fuel combustion in thousand tons	1971–2018	IEA CO_2 Emissions from Fuel Combustion Statistics [23]

Source: Our elaborations.

$$R^{\prime}{}_{t}(s) = \frac{\left|S(s^{-1}w_t^{xy}(s)\right|^2}{S(s^{-1}\left|w_t^x(s)\right|^2)S(s^{-1}\left|w_t^y(s)\right|^2} \tag{2}$$

The wavelet coherence can be interpreted as a correlation coefficient with a value range between 0 and 1, s denotes the smoothing parameter. In the no smoothing case, the wavelet coherence will be equal to 1. The squared wavelet coherence coefficient belongs to the range $0 \leq R^2\ (u,s) \leq 1$ and values close to 0 indicate weak correlation and that close to one confirms the presence of high correlation. Thus, the wavelet coherence can be seen as a convenient instrument to measure the selected variables correlation over time.

Following Torrence and Compo [68] and Grinsted et al. [67], we applied the smoothing operator S as:

$$\mathrm{S(W)=S_{scale}(S_{time}(W_n(S)))} \tag{3}$$

Where S_{scale} denotes smoothing along the wavelet scale axis and S_{time} smoothing in time. It is natural to design the smoothing operator so that it has a similar footprint as the wavelet used. For the Morlet wavelet, a suitable smoothing operator is given by Torrence and Webster [66].

$$S_{time}(W)s = \left(W_n(s) * x_1^{\frac{-t^2}{2s^2}}\right)s \tag{4}$$

$$S_{time}(W)s = (W_n(s) * x_2 \prod(0.6s))n, \tag{5}$$

Where S_{time} denotes smoothing in time, W denotes frequency (bandwidth), x_1 and x_2 are normalisation constants and Π is the rectangle function, n denotes dimensionless time. The factor of 0.6 is the empirically determined scale decorrelation length for the Morlet wavelet (Torrence and Compo [68]). In practice, both convolutions are done discretely and therefore the normalisation coefficients are determined numerically.

Econometric Granger Causality framework

Subsequently, this wavelet methodology is followed by the Granger Causality test (GC). Applied on a Vector Auto-Regressive (VAR) model, it is thought to bring consistent causal inference results.

The effort to test for the direction of causality can be traced back to Granger [62]. The Granger-causality test is a common procedure for detecting any presence of a causal relationship between two or more variables. Thus, this test has been abundantly employed in the literature. The Granger-causality test assumes stationary series (Granger [62]). Indeed, it has been shown that using non-stationary data in causality can yield spurious and misleading causality results because the test will have non-standard distribution.

To analyse the stationarity properties of each variable, we use a range of unit root tests: the Augmented Dicky and Fuller (ADF [69]) and the Phillips and Perron (PP [70]) tests.

Since series are integrated with the same order, cointegration tests can be employed. The cointegration corresponds to a state where two or more time series are bound together in such a way that they cannot deviate from each other in the long-run.

According to the Granger representation theorem [62], if a pair of *I(1)* series are cointegrated, then a causal relationship exists in at least one direction. In this regard, the existence of a cointegrating relationship is examined with the Johansen and Juselius cointegration test [71]. To determine the direction of the causality, we apply the Granger-causality test on VAR model to the group of γ_{CO2} coefficients in Equation (6). In a nutshell, it aims at testing whether they are jointly significant or not. For instance, if $\gamma_{CO21} = \gamma_{CO22} = \ldots = \gamma_{CO2n} = 0$ then *EPC* does not Granger cause *CO2*. If the opposite is true, then electricity power consumption can be said to Granger cause CO_2 emissions. Similarly, in Equation (7), we test whether the group of δ_{GDP}, γ_{GDP}, φ_{GDP}, $\lambda_{GDP,}$ and θ_{GDP} coefficients are jointly significant or not to conclude whether CO_2 emissions, electricity power consumption, trade openness, and urbanisation cause economic growth or not, respectively. This reasoning is subsequently repeated in Equations (8)–(10). To test the causality relationship between our variables using a VAR model, the multivariate production model in the first difference forms is expressed as follows:

$$\begin{aligned}\Delta CO2_t = \alpha_1 + \sum_{i=1}^{n}\delta_{CO2i}\Delta GDP_{t-i} + \sum_{i=1}^{n}\gamma_{CO2i}\Delta EPC_{t-i} + \sum_{i=1}^{n}\lambda_{CO2i}\Delta TO_{t-i} \\ + \sum_{i=1}^{n}\theta_{CO2i}\Delta UR_{t-i} + \sum_{i=1}^{n}\varphi_{CO2i}\Delta CO2_{t-i} + \mu_{CO2t}\end{aligned} \tag{6}$$

$$\begin{aligned}\Delta GDP_t = \alpha_2 + \sum_{i=1}^{n}\delta_{GDPi}\Delta CO2_{t-i} + \sum_{i=1}^{n}\gamma_{GDPi}\Delta EPC_{t-i} + \sum_{i=1}^{n}\lambda_{GDPi}\Delta TO_{t-i} \\ + \sum_{i=1}^{n}\theta_{GDPi}\Delta UR_{t-i} + \sum_{i=1}^{n}\varphi_{GDPi}\Delta GDP_{t-i} + \mu_{GDPt}\end{aligned} \tag{7}$$

$$\begin{aligned}\Delta EPC_t = \alpha_3 + \sum_{i=1}^{n}\delta_{EPCi}\Delta GDP_{t-i} + \sum_{i=1}^{n}\gamma_{EPCi}\Delta CO2_{t-i} + \sum_{i=1}^{n}\lambda_{EPCi}\Delta TO_{t-i} \\ + \sum_{i=1}^{n}\theta_{EPCi}\Delta UR_{t-i} + \sum_{i=1}^{n}\varphi_{EPCi}\Delta EPC_{t-i} + \mu_{EPCt}\end{aligned} \tag{8}$$

$$\begin{aligned}\Delta TO_t = \alpha_4 + \sum_{i=1}^{n}\delta_{TOi}\Delta GDP_{t-i} + \sum_{i=1}^{n}\gamma_{TOi}\Delta EPC_{t-i} + \sum_{i=1}^{n}\lambda_{TOi}\Delta CO2_{t-i} \\ + \sum_{i=1}^{n}\theta_{TOi}\Delta UR_{t-i} + \sum_{i=1}^{n}\varphi_{TOi}\Delta TO_{t-i} + \mu_{TOt}\end{aligned} \tag{9}$$

$$\begin{aligned}\Delta UR_t = \alpha_5 + \sum_{i=1}^{n}\delta_{URi}\Delta GDP_{t-i} + \sum_{i=1}^{n}\gamma_{URi}\Delta EPC_{t-i} + \sum_{i=1}^{n}\lambda_{URi}\Delta TO_{t-i} \\ + \sum_{i=1}^{n}\theta_{URi}\Delta CO2_{t-i} + \sum_{i=1}^{n}\varphi_{URi}\Delta UR_{t-i} + \mu_{URt}\end{aligned} \tag{10}$$

where Δ represents the first difference and μ_{CO2t}, μ_{GDPt}, μ_{EPCt}, μ_{TOt} and μ_{URt} are white noise error processes. The lag-selection has been performed following the Akaike's Information Criterion (AIC), the Schwarz's Bayesian Information Criterion (SBIC), the

Hannan-Quinn Information Criterion (HQIC), the Final Prediction Error (FPE), and the Log-Likelihood (LL).

Empirical results and discussion

Descriptive statistics

Table 4 shows the descriptive statistics of the selected variables. The measures of kurtosis indicate that distributions of *CO2, GDP, EPC, TO* and *UR* are away from the standard values of a normal distribution. Hence, our empirical wavelet procedure can be adequately applied.

Results of the wavelet analysis: correlation evidence

Figures 2–5 show the analysis of wavelet coherence between CO_2 and independent variables (*EC, GDP, TO*, and *UR*) in KSA. The *x*-axis in the figures displays the time period and the *y*-axis shows the frequency at three different scales: high, medium, and low, coding for long-, medium-, and short-run, respectively. In the wavelet coherence, the shape of cone white line is called 'the cone of influence'. The colour scale on the right side is determinant to interpret the significance of the correlating relationship among variables. Higher correlation between the variables is presented by hotter colours with respect to R^2; and the 5% significance level is indicated by the thick black shape in the figures. The characteristic of the correlation forces between the variables can be indicated by the arrow direction. Therefore, it could be determined whether the variable was lagging or leading. Thus, the arrow pointing to the right indicates a positive correlation among the variables. The arrow pointing to the left indicates evidence of a negative correlation.

The present study seeks to go beyond the analysis of correlating relationships and aims at providing evidence of causality inferences among variables. Thus, in Section 4.3., we further enrich the present wavelet procedure with a causality testing framework (i.e. the Augmented Dicky and Fuller (ADF) and the Phillips and Perron (PP) tests, the Johansen and Juselius cointegration test, and the Granger Causality test (GC), applied on a Vector Auto-Regressive (VAR) model).

Displayed in Figure 2, the results of the wavelet analysis for *GDP* and *CO2* are highly interesting. Above all, findings indicate the existence of a positive and significant correlation between *GDP* and *CO2* on the long run in KSA. Indeed, for the whole 1971–2018 period, the arrows are mostly rightward pointing in the thick black shape

Table 4. The descriptive statistics of all variables.

Variables	Mean	Median	SD	Min	Max	Skewness	Kurtosis
CO2	223639.6	192329.8	157154.6	12678.68	531393.7	0.560684	2.229156
GDP	22817.65	19675.92	7123.134	15695.18	39152.08	1.289353	3.086959
EPC	8848.145	6521.324	8355.48	165.6922	26737.66	0.944142	2.736247
TO	78.58865	75.08743	11.45377	56.08838	96.13822	−0.227085	1.836261
UR	74.51329	78.5495	9.277165	50.6882	83.8441	−1.131431	3.085464

Sources: Our calculations based on WDI [7] and IEA [22,23] data.
Notes: SD: Standard Deviation; Min: Minimum Value; Max: Maximum Value.

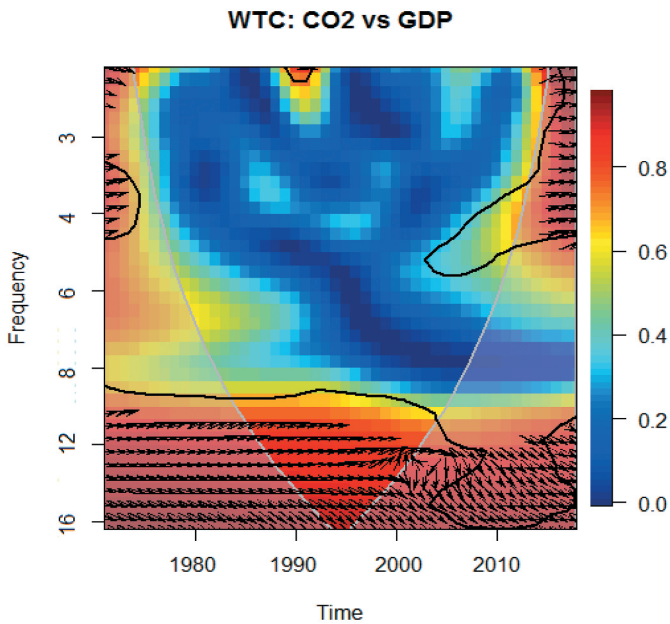

Figure 2. Wavelet analysis for *CO2* and *GDP*. Source: Our elaborations with WDI [7] and IEA [22,23] data.

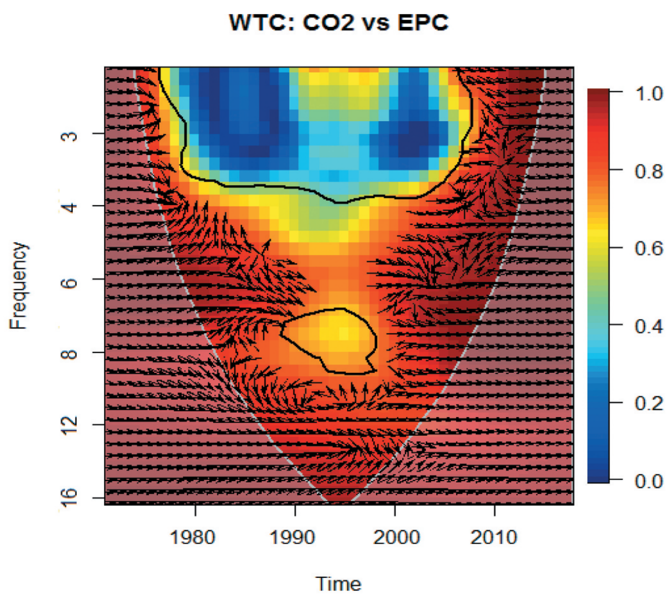

Figure 3. Wavelet analysis for *CO2* and *EPC*. Source: Our elaborations with WDI [7] and IEA [22,23] data.

area. Hence, this confirms the presence of a positive relationship shared by *GDP* and *CO2* indicators at a high scale (long run). Nonetheless, it is important to compare the long-run results with those obtained at the lowest scale, and where no evidence of short-run correlation between *CO2* and *GDP* is found for the 1975–1990 and 1995–2010 periods,

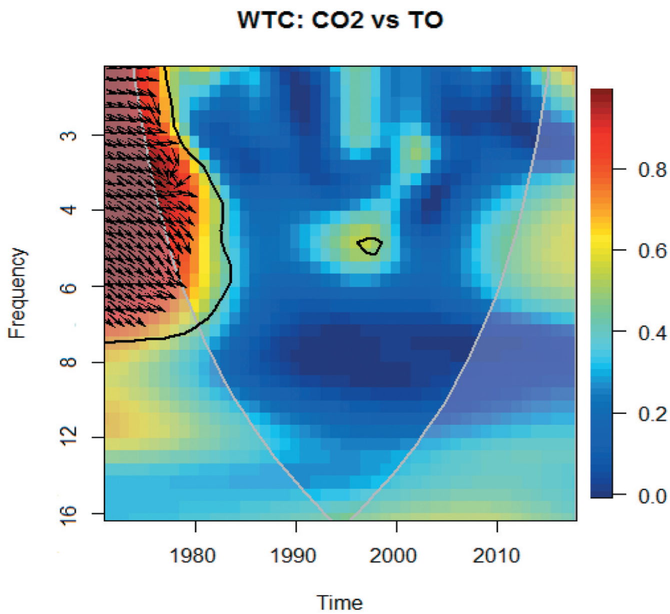

Figure 4. Wavelet analysis for *CO2* and *TO*. Source: Our elaborations with WDI [7] and IEA [22,23] data.

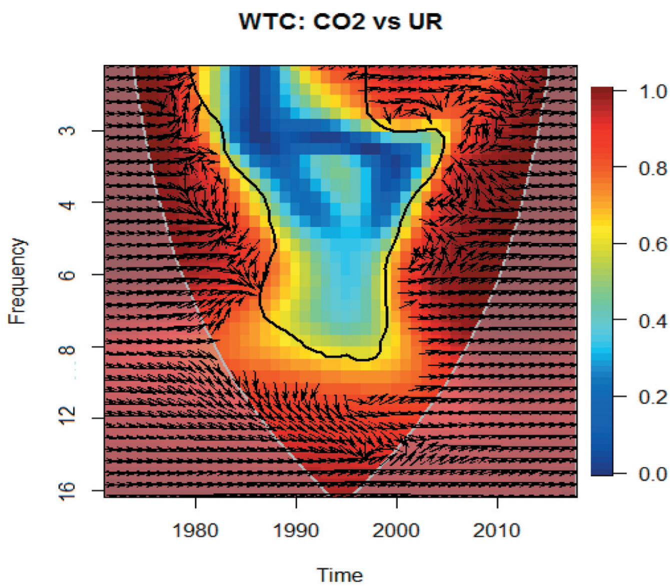

Figure 5. Wavelet analysis for *CO2* and *UR*. Source: Our elaborations with WDI [7] and IEA [22,23] data.

contrasting thus with the 1990–1995 and 2010–2018 periods. That can be explained by the high oil revenues in KSA. In fact, the economy is highly dependent on oil revenues which are just as sensitive to the fluctuation of oil prices.

Having reached high levels in the past decade, oil prices have been associated with a booming of the revenue in the oil sector; and thus a rise of per capita income which has profoundly changed the consumption pattern of households in KSA. Indeed, the current consumption habits are shifting from low emission–intensive services and goods to more energy and emission intensive ones. This can be understood when taking the oil price shock that occurred after the financial crisis of 2008 as an example. Indeed, it had several economic (and sometimes unexpected) consequences. But it has increased the average household incomes by about 75% in KSA, making this economy the world's 19th largest one worldwide. As a result, the country's GDP has been doubled, and 1.7 million jobs have been created. Such structural breaks may undoubtedly be linked with the serious CO_2 emissions rise recorded these recent years. These results of the relationship between GDP and CO_2 emissions are in line with those of Raggad [58] for KSA; and see Ehigiamusoe and Lean [72]; Farhani et al. [41]; and Bekhet et al. [48], for GCC countries. This contradicts Seetanah et al. [73] and Hossain and Hasanuzzaman [74]. Accordingly, any economic strategy adopted by the KSA should consider the income factor to lower adverse environmental effects.

Figure 3, shows the results of wavelet coherence between *CO2* and *EPC*. Related outputs indicate the existence of a positive and significant correlation between *CO2* and *EPC* at medium and high scales. Indeed, looking at the 1971–2018 period, one observes from the related figure that the arrows are mostly rightward pointing in the thick black shape area. Compared to the results obtained at the low scale, evidence of such correlation relationship is less robust. On the short-run (low scale), although a positive correlation emerges between *EPC* and *CO2* for the 1971–1978 period, no evidence can be provided for the 1978–2005 period. Nonetheless, such relationship is less robust for low and medium scales. Indeed, given our long and medium scale findings, increasing the consumption of electricity is associated with an increase in CO_2 emissions in KSA, which in turn, may contradict the sustainability pattern. The positive effect of electricity production on environmental degradation may have several cofounding explanations (the elevated population growth rate, the high GDP growth, the relatively low prices of electricity and energy, warm climate and the lack of efficient technology to produce power). The government should take strong measures to mitigate the externalities induced by non-renewable energy use.

KSA still generated 76.2% of its electricity from oil, natural gas, and coal in 2015 [7]. To meet the environmental challenges facing KSA, an increase of the share of renewables in the total electricity supply is necessary. To shift from fossil to renewable sources of energy requires time, technologies, and an important fixed cost. This explains why generating power based on nuclear and natural gas is considered as a means of providing a low-carbon alternative to electricity from oil and coal [31,75–77]. In addition, developing renewables cannot be achieved without adequately skilled and technical manpower, a general problem in developing countries [78–80]. This is in line with Sari et al. [81] who underlined that labour is a key driver of conventional hydroelectric power, solar, waste, and wind energy development in the US. Nonetheless, enhancing the share of renewables may also produce several benefits. A strand of the literature has demonstrated its economic and employment effects for various country cases. According to the Annual Review published by the International Renewable Energy Agency [82], renewable energy technologies may have created more than 11 million direct and indirect jobs worldwide in 2018. Some studies have highlighted the cost-efficiency characteristics of adopting renewable energy. Farnoosh et al. [83] showed that, if KSA reaches an optimal generation mix structure in the near future (i.e.

50% of power from renewables and nuclear power plants and 50% from the fossil power plants), the reduction of the total cost of power generation can reach 28% per year from 2030. These results on the positive correlation between electricity consumption and CO_2 emission agree with those of Raggad [61] for KSA; Flores-Chamba et al. [84] for the European Union; Wang et al. [85] for the case of 186 countries; Zaidi et al. [86] for APEC states.

Figure 4, presents the results for the *CO2-TO* relationship. The obtained results show evidence of mixed correlation between *CO2* and *TO*. At the low scale, the arrows are mostly rightward pointing in the thick black shape area over the period 1971–1980. This confirms the existence of a short-run positive correlation between *TO* and *CO2*. At the medium scale, a similar output is depicted over the 1971–1985 period. Finally, high-scale evidence is scarce and sporadic indicating that such conclusion cannot be supported in the long-run. Globally, such mixed results on the *CO2-TO* relationship can be interpreted as follows: until the mid 1980s, a positive correlation between trade openness on CO_2 emissions is supported at low and medium scales, but a less consistent relation then follows, becoming negligible during the most recent years.

It can be argued that the relationship between trade openness and CO2 emissions is weakly consistent and cannot cover the long-run perspective. The results obtained are in line with those of Mutascu [24] in the case of France, who indicated that there is a positive relationship between TO and CO2 on the low and medium run, but not on the long run. Yet this contradicts Sebri and Ben-Salha [26] who showed that international trade may facilitate the transfer of renewable technologies and thus help decarbonise the power sector. It could be concluded that *TO* has a very weak positive correlation with *CO2*, since most of the time there is no evidence of such relationship.

Such mixed results might still be partly explained by the heavy reliance on using fuel and other natural resources in the process of trade in KSA. Indeed, regarding exports, the national oil industry displays one of the largest oil exporting capacities worldwide. In addition, a significant amount of embodied emissions can be found in the KSA imports. Trade openness may increase the domestic demand for foreign CO_2 intensive goods in KSA[9] [87,88]. Nonetheless, these emissions are formally unrecorded for KSA but accounted for in the exporting country. Accordingly, our weakly consistent results do not confirm the existence of a robust trade-CO2 relationship in KSA. This contradicts Ansari et al. [89] for the top CO_2 emitters worldwide; Saidi and Mbarek [90] for 19 emerging countries; Oh and Bhuyan [91] for Bangladesh; Saud et al. [92] for the case of the Belt and Road Initiative; and Afridi et al. [93] for the SAARC region, and in which trade is found to mitigate CO_2 emissions.

Figure 5 shows results of wavelet coherence between *CO2* and *UR* for KSA. They show that the arrows are mostly rightward pointing in the thick black shape area over the 1971–1985 period. Hence, this confirms that *UR* and *CO2* are positively correlated at low to medium scale 0–8 years. But from 1985 to 2000, no correlation forces are depicted between *CO2* and *UR* at low and medium scales. This disagrees with the output observed over the 2000–2018 period where the arrows are mostly rightward pointing in the thick black shape area. According to Parikh and Shukla [94], urbanisation is part of the economic cycle. Hence, such results are not surprising; they have theoretical explanations. Urbanisation (development in cities) requires many construction projects, because people will be more attracted to those more modern parts in a country. Such development leads to a huge environmental burden as these projects need fuel and natural resources. Another explanation for the positive relationship between urbanisation and CO_2 emissions in KSA is decidedly the oil industry, among the biggest in the world. Thus, the urban planning in KSA has been driven by the needs (i.e. employment and infrastructure) of the oil industry to allow the labour migration from rural to urban areas [95]. This finding agrees with Tamura et al. [96], Ali et al. [97], and Alvarado et al. [98] but contradicts Asane-Otoo [99]. All in all, it emphasises the results of Magazzino et al. [100] on the cofounding effect of urbanisation on GHG emissions from the waste sector.

The results of the present study, although their respective effects differ, demonstrate that electricity consumption, income, and urbanisation are positively correlated with the emissions of carbon dioxide in KSA. Besides being mixed, the correlation between trade openness and environmental pollution appears weakly significant and becomes negligible over time. Table 5 summarises the empirical findings drawn from the wavelet analysis.

Results of the Granger Causality test applied on a vector auto-regressive (VAR) model: causal inferences

To test the stationarity properties of the times series *CO2, GDP, EPC, TO*, and *UR*, the Augmented Dicky-Fuller (ADF [69]), and the Phillips-Perron (PP [70]) tests are employed. Table 6 shows the results. All proposed tests results indicate that each series requires a first-difference transformation to attain stationarity. Thus, this confirms that both variables are *I(1)*: their levels are not stationary but their first differences are.

Table 7 shows the Johansen and Juselius [71] cointegration test results. Here, we have ample evidence of the existence of one cointegrating relationship between the series *CO2, GDP, EPC, TO*, and *UR*, in KSA.

The evidence of a cointegrating relationship implies causality (in the sense of Granger [62]) in at least one direction. Selection of the appropriate lag length is necessary for the VAR model: the appropriate lag length of 1 is selected based on the Akaike's Information Criterion (AIC), the Schwarz's Bayesian Information Criterion (SBIC), the Hannan-

Table 5. Summary of the wavelet results.

Variables	Frequency	Significance of the Correlation	Strength of the Correlation
GDP-CO2	Low	GDP↔CO2(Yes)	Weak
	Medium	GDP↔CO2(No)	Null
	High	GDP↔CO2(Yes)	Strong
EPC-CO2	Low	EPC↔CO2(Yes)	Weak
	Medium	EPC↔CO2(Yes)	Strong
	High	EPC↔CO2(Yes)	Strong
TO-CO2	Low	TO↔CO2(Yes)	Weak
	Medium	TO↔CO2(No)	Null
	High	TO↔CO2(No)	Null
URB-CO2	Low	UR↔CO2(Yes)	Strong
	Medium	UR↔CO2(Yes)	Strong
	High	UR↔CO2(Yes)	Strong

Source: Our elaborations.

Notes: GDP, CO_2, EPC, TO, UR, refer to economic growth, CO_2 emissions, electricity power consumption, trade openness and urbanisation, respectively. A↔B(Yes) indicates that the correlating relationship between A and B is significant. A↔(No)B indicates that the correlating relationship between A and B is insignificant and negligible.

Table 6. Results for unit root and stationarity tests.

variables	Augmented Dicky Fuller (ADF) test constant	MacKinnon approximate *p*-value	Phillips-Perron (PP) test constant	MacKinnon approximate *p*-value
CO2	−0.432 (1)	[0.9047]	0.430 (1)	[0.9826]
ΔCO2	−3.456 (1)	[0.0092]	−3.456 (1)	[0.0092]
GDP	−1.691 (1)	[0.4360]	−1.319 (1)	[0.6204]
ΔGDP	−5.421 (1)	[0.0000]	−5.421 (1)	[0.0000]
EPC	−0.463 (1)	[0.8990]	2.507 (1)	[0.9991]
ΔEPC	−3.837 (1)	[0.0026]	−3.837 (1)	[0.0026]
TO	−1.979 (2)	[0.2957]	−0.760 (2)	[0.8305]
ΔTO	−10.339 (1)	[0.0000]	−10.339 (1)	[0.0000]
UR	−2.248 (1)	[0.1894]	−16.29 (1)	[0.0000]
ΔUR	−3.841 (1)	[0.0025]	−3.066 (1)	[0.0292]

Source: Our elaborations.
Notes: the tests are performed on the levels of the variables. ADF [69]: Augmented Dicky-Fuller test [69]; PP [70]: Phillips-Perron test [70]. When it is required, the lag length is chosen according to the SBIC. Figure in the parenthesis is the optimal lag structure for ADF test, and bandwidth for the PP test. Probability values are given in brackets. ***$p < 0.01$, **$p < 0.05$, *$p < 0.10$.

Table 7. Johansen and Juselius [71] cointegration tests results.

number of cointegrating equations	Parms	LL	Eigenvalue	Trace Statistic	5% Critical Value
0	8	265.88496	0.00	50.8821	54.64
1	15	277.8626	0.51612	31.9268*	34.55
2	20	287.68833	0.44871	12.2754	18.17

Source: Our elaborations.
Notes: * indicates the number of cointegrating equations.

Table 8. Granger causality test [62] results.

Equation	Excluded	*F*	*P*-value
ΔCO2	ΔGDP	5.9836**	0.0210
ΔCO2	ΔEPC	7.5984**	0.0102
ΔCO2	ΔTO	3.4228*	0.064
ΔCO2	ΔUR	6.2161**	0.013
ΔCO2	ALL	15.999***	0.003
ΔGDP	ΔCO2	0.14402	0.704
ΔGDP	ΔEPC	10.5140***	0.0031
ΔGDP	ΔTO	11.886***	0.001
ΔGDP	ΔUR	0.84181	0.359
ΔGDP	All	12.933**	0.012
ΔEPC	ΔCO2	2.5494	0.110
ΔEPC	ΔGDP	0.04564	0.831
ΔEPC	ΔTO	0.28708	0.592
ΔEPC	ΔUR	0.2079	0.648
ΔEPC	All	4.103	0.392
ΔTO	ΔCO2	0.37122	0.542
ΔTO	ΔGDP	2.4984	0.114
ΔTO	ΔEPC	1.1336	0.287
ΔTO	ΔUR	0.00097	0.975
ΔTO	All	3.7326	0.443
ΔUR	ΔCO2	0.5496	0.458
ΔUR	ΔGDP	1.1177	0.290
ΔUR	ΔEPC	0.17142	0.679
ΔUR	ΔTO	6.5326**	0.011
ΔUR	All	8.4309*	0.077

Source: Our elaborations.
Notes: ***$p < 0.01$, **$p < 0.05$, *$p < 0.10$.

Table 9. Summary of the Granger Causality results.

Relationship	Direction of the Causality	Statistical Significance
GDP-CO2	GDP→CO2	5% level
EPC-CO2	EPC→CO2	5% level
UR-CO2	UR→CO2	5% level
TO-CO2	TO→CO2	10% level
EPC-GDP	EPC→GDP	1% level
TO-GDP	TO→GDP	1% level
TO-UR	TO→UR	5% level

Source: Our elaborations.
Notes: GDP, CO_2, EPC, TO, UR, refer to economic growth, CO_2 emissions, electricity power consumption, trade openness and urbanisation, respectively. A → B indicates the existence of a unidirectional causality from A to B.

Quinn Information Criterion (HQIC), the Final Prediction Error (FPE) and the Log-Likelihood (LL).

Table 8 shows the results of the Granger-causality test applied on Vector-Autoregressive (VAR) model. The first row shows that lagged value of *GDP* causes *CO2* as P-value is equal to 0.0210. Therefore, the null hypothesis that lagged value of *GDP* does not cause *CO2* can be rejected at the 5% significance level. We thus have ample evidence of a causality running from economic growth to CO_2 emissions. In addition, our findings confirm the existence of a causality running from electricity power consumption to CO_2 emissions. Indeed, the second row showing that lagged value of *EPC* does not cause *CO2* has a P-value that is equal to 0.0102. Thus, the null hypothesis 'lagged value of *EPC* does not cause *CO2*' can be rejected. Furthermore, with a p-value of 0.013 and 0.064, a significant causal relationship is established from *UR* to *CO2*, as well as from *TO* to *CO2*, respectively. The null hypothesis that lagged value of *TO* does not cause *CO2* can only be rejected at 10% level. With closer examination, a significant causal relationship is also observed from *EPC* to *GDP*, but not vice versa. Congruent with the '*growth hypothesis*', this indicates that KSA's economy might be an electricity-dependent one, and any policies aiming to reduce power consumption might adversely impact economic growth. Finally, the lagged value of *TO* causes *GDP* as P-value is equal to 0.001, providing evidence that trade openness causes economic growth without feedback.

In line with our wavelet results (see sub-Section 3.2.), the above-mentioned indicators reveal crucial linkages. Further, our econometric findings confirm the output drawn from our Wavelet analysis and provide causality evidence. Accordingly, a significant causal relationship running from economic growth to CO2 emissions is established. Congruent with our Wavelet procedure, electricity consumption and urbanisation are (a) found to be significantly linked and (b) to drive carbon emission growth in KSA. Overall, trade openness displays a causal nexus with CO_2 emissions, although its weak significance (i.e. 10% level) makes this result less reliable. Far from being a coincidence, this corroborates the Wavelet results previously obtained as mixed and weak correlation evidence have been reported between *CO2* and *TO*. Table 9 summarises the causality findings drawn from the econometric analysis.

Conclusion and policy implications

This paper is the first to explore the relationship between electricity consumption, economic growth, urbanisation, trade openness and CO_2 emissions for the single case of the Kingdom of Saudi Arabia (KSA). We employed a wavelet coherence approach as it can decompose time-series into different time scales and thus depict the correlation forces amongst variables. Inversely, simply analysing the data with linear instruments may provide misleading results as it hides the cofounded factors which might influence the observed relationships. In keeping with this innovative methodology, we use time-series data covering the most recent and available period: 1971–2018. Although this empirical strategy has not been applied to this topic so far, it brings consistent correlating evidence with far-reaching policy implications for KSA. Finally, to give evidence of causal inferences among variables, stationary (the Augmented Dicky and Fuller (ADF) test; the Phillips and Perron (PP) test) and cointegration (the Johansen and Juselius cointegration test) procedures are followed by the Granger Causality test (GC), applied on a Vector Auto-Regressive (VAR) model.

The wavelet results supported the existence of a positive correlation between per capita income and CO_2 emissions on the long-run, but findings are weakly significant on the short- and medium-runs. In addition, the Granger Causality test reveals the existence of a unidirectional causal relationship running from per capita income to CO_2 emissions. Similarly, electricity consumption is statistically correlated with CO_2 emissions on the medium and long runs, while our econometric procedure which supports the existence of a one-way causal link from electricity consumption to carbon emissions without feedback. However, our wavelet-related results do not provide such evidence for trade openness. Finally, urbanisation and CO_2 emissions appear highly correlated at all scales (short-, medium- and long-runs), and a unidirectional causality emerges among variables. All in all, a one-way causality is also observed from electricity consumption to economic growth. Congruent with the '*growth hypothesis*', it indicates that KSA's economy might be an electricity-dependent one. Thus, any policies aiming to reduce the consumption of power might adversely impact economic growth.

In view of policy implications, it is advisable to address the carbon emissions issue through adequate measures in KSA. Although electricity conservation policies may lower the production of harmful emissions, conservation should be accompanied by a complete shift from non-renewable to renewable resources of energy. Constituting the global long-run reform of the energy system of any country, building a low-carbon power sector obviously requires time, capital, and technologies. Hence, a hybrid electricity supply should be attained on the medium-term, in which renewables may be a significant share. This optimal power generation mix in KSA should reach 50% of power from renewables and nuclear power plants and 50% from the fossil power plants by 2030.

This would ensure the long-run sustainability of the national power supply but also reduce the critical dependence of KSA on fossil products. This is in line with the Saudi government's Vision 2030 launched in 2016 which aims to restructure the Saudi economy away from its reliance on oil. Since the economic output produced for every kilogram of oil equivalent consumed is about US$ 3.70 (which is far from the global average US$ 6.20), massive investments in efficiency technologies should be proposed, with direct application in local power plants and the most intensive sectors (including transport and household infrastructures). As it is known that enhancing trade flows increases the consumption of energy (mostly fossil fuels for transport and industry purposes) and pollutants, policies should target the development of green practices along the supply chain in KSA, with a specific focus on the establishment of low-carbon production activities. Innovation could also play a valuable role. This could not only reduce the environmental externalities but also boost long-term business profitability.

Future studies should assess the electricity consumption-carbon emissions nexus in KSA at sectoral level. If data availability allows that, it would bring finer insights by identifying the less energy efficient industries among sectors.

Notes

1. CO_2 is the source of more than 60% of the world's greenhouse effect [101].
2. CO_2 emissions increased from 169,404 to 563,449 kilotons over the period 1980-2016 in KSA [8].
3. An exhaustive review on the renewable energy potential of KSA can be found in Alnatheer [19].
4. The Saudi government's Vision 2030 launched in 2016 intends to restructure the economy away from its dependence on oil through the development of new industries and business sectors [21].
5. See Cifter and Ozun [102] on Turkey; Aslan et al. [33] for the United States (US); Ha et al. [103] for China, and Matar [104] for the Gulf Cooperation Council (GCC) countries.
6. Urbanisation, trade openness and GDP data are available at: https://databank.worldbank.org/source/world-development-indicators.
7. Electricity consumption data are available at: https://www.oecd-ilibrary.org/energy/data/iea-world-energy-statistics-and-balances/world-energy-balances_data-00512-en
8. CO_2 emissions from fuel combustion data are available at: https://www.oecd-ilibrary.org/energy/data/iea-co2-emissions-from-fuel-combustion-statistics/co2-emissions-by-product-and-flow_data-00430-en
9. For an input-output analysis of CO_2 emissions embodied in trade, see Su and Ang [87].

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