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Research article

Impacts of renewable and disaggregated non-renewable energy consumption on CO2 emissions in GCC countries: A STIRPAT model analysis

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A R T I C L E I N F O

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A B S T R A C T

This research investigates the effects of renewable (REC) and disaggregated non-renewable energy consumption (coal, oil, and natural gas) on CO2 emissions (CO2) in GCC countries, employing the STIRPAT model. The research also compares the impact of various non-renewable energy (NREC) sources to identify their contributions to CO2 emissions. Demographic factors like population and economic growth are considered main determinants of CO2. Panel data econometric methods are used, including diagnostic tests and unit root tests, to found long-run relationships among the variables. The study reveals significant positive associations between coal, natural gas, oil consumption and CO2, with oil having the highest impact. Conversely, REC shows a significant negative correlation with CO2. Economic growth and population are also linked to increased CO2. The findings emphasize the need for strategies promoting renewable energy usage, energy efficiency, public transportation, carbon pricing, and research in green technologies to alleviate CO2 and enhance sustainable development in the GCC countries.

1. Introduction

Economic growth holds a crucial role for nations across the spectrum, encompassing developed, developing, and emerging economies. Moreover, the pursuit of sustainable economic growth assumes paramount importance in advancing global sustainable development objectives. Economic growth requires sufficient energy to ensure sustainable development [1]. This is why energy plays a crucial role in various facets of economic endeavors, including production, consumption, transportation, and more, involving participants in the economy [2]. To achieve greater economic growth, there is an increasing demand for higher energy consumption. Nevertheless, in recent times, the issue of environmental degradation has emerged as a significant concern among countries

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experiencing economic growth. Consequently, environmental degradation has shifted to the forefront of academic discourse, garnering significant attention from researchers and policymakers [3,4].

Recent studies have highlighted the correlation between industrial structure and carbon footprint, suggesting that a primary industry-dominated structure leads to higher carbon emissions compared to one where tertiary industry predominate. Also, the value creation of primary industries is less energy efficient than the tertiary level, and higher levels of environmental damage are expected. Given the significant energy input required for economic output, transitioning from fossil fuel-based sources to renewable energy is crucial. Promoting renewable energy sources and energy efficiency can help reduce carbon emissions and mitigate environmental harm. Furthermore, the role of tertiary industries, such as service-oriented businesses, in reducing carbon footprint should be emphasized [5].

According to the existing literature, energy sources can be classified as renewable and nonrenewable [6]. Environmental deterioration primarily results from the utilization of fossil fuels for energy production. Many countries possess the capacity to tap into sustainable energy sources like wind and solar power, as alternatives, to avoid using other energy sources [7–9]. The utilization of fossil fuels significantly contributes to environmental degradation by causing a rise in CO2 [10–12]. On the other hand, the usage of renewable sources has surged in the contemporary era. Based on existing research, renewable energy sources have a vital role in reducing CO2 emissions. This reduction stems from their natural generation and the fact that their utilization does not contribute to CO2 emissions [13,14]. The proportion of energy generated from fossil fuels has significantly risen, while the utilization of renewable energy sources is steadily growing [15].

The surge in energy consumption within Gulf Cooperation Council (GCC) nations, constituting a significant 34 % of the overall energy-linked pollution in the area, can be attributed to sectors like steel, iron, cement, aluminum production, and construction [16,17]. Despite a decline in energy consumption in 2010, GCC states still consume a huge quantity of energy, despite having relatively small populations. In fact, their utilization of oil and natural gas exceeds that of Japan and Indonesia, surpassing the total primary energy consumption of the entire African continent [18]. Fig. 1 shows the fossil fuel consumption by source in GCC for the period 1995 to 2017. In 2017, the demand for oil surged by 1.7 million barrels per day (Mb/d). This growth was comparable to the rise observed in 2016 and notably higher than the 10-year average, which typically stood at approximately 1.1 Mb/d [19]. The using of natural gas in GCC region has shown a continuous rise, as the consumption of natural gas for these countries in 2017 amounted to (9.62 EJ) an increase of (0.17 EJ) over the year 2016 that was (9.45 EJ) [20]. As the consumption of coal for the GCC countries in 2017 amounted to (0.11 EJ) an estimated increase of (0.02 EJ) over 2016 that was (0.09 EJ) [21]. In a broader perspective, while GCC nations are home to just 0.6 % of the global population, they account for as much as 2.4 % of the global total greenhouse gas emissions.

The usage of renewable energy has already become a well-established option for the region as an alternative solution to reduce its dependency on fossil fuels [22]. Solar energy is readily available in onshore areas, and offshore locations offer an abundance of wind energy sources [22]. This growing demand for desalinated water, electricity generation, and recycling initiatives, combined with the cost-effectiveness of solar and wind energy, has sparked a renewed focus on renewable energy in the GCC [23]. Furthermore, renewable energy offers a viable avenue for repurposing the substantial financial surpluses generated from oil production, allowing for potential exportation of energy to Europe's grid [23,24]. The significant surge in electricity demand can be attributed to the rapid population growth and strong economic development observed in the region. Consequently, governments in the Gulf Cooperation Council (GCC) region began to explore opportunities presented by affordable energy sources and initiated a review of their taxation policies [25,26]. Despite the global adoption and growing cost competitiveness of wind and solar power in the energy landscape, GCC policymakers have been relatively slow to embrace these renewable energy sources. This cautious approach can be linked to the region's limited prior experience in executing renewable energy initiatives. Fig. 1 illustrates the use of nonrenewable energy in GCC

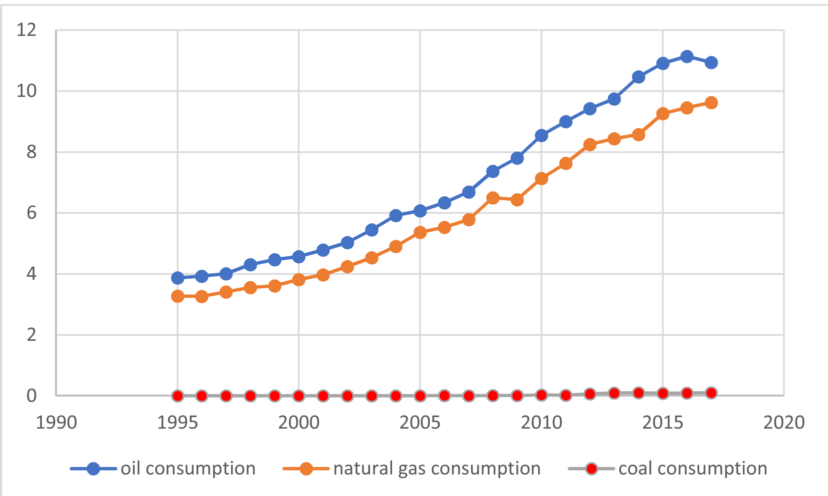

Fig. 1. Oil, gas, coal consumption (Exajoules) for GCC countries (1995–2017).
Source: BP statistics 2021

countries from 1995 to 2017.

The need to explore the linking between the consumption of energy and CO2 in the GCC region becomes evident when we consider the extensive body of literature addressing the relationships between the use of energy and economic growth [1,27]. These researches have recognized that the consumption of energy, particularly in the form of oil, coal, and natural gas, plays a role in driving economic growth. However, concurrently, it generates an adverse environmental impact, including the release of CO2 and other greenhouse gases. Furthermore, these prior research has also provided empirical indication demonstrating bidirectional causal links between the use of these energy resources, economic expansion, and environmental pollution [28,29]. Nevertheless, within the framework of a significant emerging economy such as the GCC, there is a noticeable scarcity of empirical research addressing the coexistence and cause-and-effect relationships among different forms of nonrenewable consumption, economic expansion, and greenhouse gas. Consequently, it becomes imperative to undertake investigations focusing on these interconnections, aiming to unearth novel insights and derive actionable policy recommendations in the context of reducing emissions within the GCC.

Given this background, the current study seeks to investigate the impact of natural gas, coal, and oil consumption, along with the utilization of renewable energy sources, on CO2 emissions. This analysis considers factors such as energy consumption, economic growth, and population, within the situation of the GCC, utilizing annual data spanning from 1995 to 2017. This study distinguishes itself from prior research in several notable aspects. Firstly, it delves into the correlation between individual fossil fuel consumption and CO2 emissions within the GCC region, a topic that has received limited attention in existing literature. Previous studies have predominantly focused on the overall impact of energy consumption on CO2 emissions in the GCC. Secondly, while some prior research has explored the link between CO2 emissions and various energy-related factors, many of these studies assume independence among cross-sectional residuals and uniformity among individual slope coefficients. However, this assumption may yield inaccurate estimation outcomes in the presence of cross-sectional dependencies and heterogeneity among slope coefficients. In contrast, our study acknowledges the existence of such dependencies and heterogeneities. Consequently, we employ recently developed econometric methods that address these challenges in the estimation process, ensuring the accuracy and reliability of our findings. Finally, our study adopts a comprehensive approach by offering extensive and inclusive policy recommendations for mitigating CO2 emissions while fostering economic growth, particularly within the context of the GCC.

The subsequent sections of this paper are structured as follows: The first section presents the study's data and theoretical framework. The second section outlines the empirical methodology. The third section presents the empirical results and discussions. Finally, the last section summarizes the key findings of the study.

2. Data description and theoretical model specification

The study relies on empirical research conducted on information pertaining to five countries that are members of the GCC. These countries include Oman, United Arab Emirates, Kuwait, Qatar, and Saudi Arabia. As data for the majority of these countries was not accessible prior to 1995, the research period analyzed spans from 1995 to 2017. The main focus of this paper is to thoroughly examine the connections between CO_2 emission and its energy use proposed determinants in a multivariate structure. Econometrically, the dependent variable (CO_2), is the carbon dioxide emissions measured in kilotons (kt). CC, OC, and NGC are the final coal, oil, natural gas consumptions measured in (Exajoules), respectively. RE represents the ratio of renewable energy use in relation to the final energy use, while EC quantifies final energy use in KG of oil equivalent. GDP denotes the Gross Domestic Product in constant 2015 US dollars, and POPU represents the total populations for each country in GCC countries. All the variables employed this current study were log-transformed so as to construe their respective parameter estimates as elasticities of CO_2 emission in the long-term steadiness. Table 1 provides a concise overview of the variable descriptions and their respective data sources.

Our aim is to explore the connection between key variables, specifically CO2 and the breakdown of energy sources into renewable and nonrenewable components, while also considering the variables of economic growth and population in GCC nations. To achieve this goal, The Stochastic Impacts by Regression on Population, Affluence, and Technology (STIRPAT) model serves as a foundational tool in our exploration of the intricate connections between key variables such as CO2 emissions and the breakdown of energy sources into renewable and nonrenewable components, while also considering economic growth and population dynamics within the Gulf

Table 1
Data description and sources.

Variables	Symbol	Sources	The description
Carbon dioxide emission	CO_2	World Development Indicators (https://data.worldbank.org)	CO_2 emitted from fuel consumption (kilotons kt)
Coal consumptions	CC	BP statistics (http://www.bp.com/statisticalreview)	Final Coal consumption measured by Exajoules
Oil consumptions	OC	BP statistics (http://www.bp.com/statisticalreview)	Final oil consumption measured by Exajoules
Natural gas consumptions	NGC	BP statistics (http://www.bp.com/statisticalreview)	Final natural gas consumption measured by Exajoules
Renewable energy consumption	RE	World Development Indicators (https://data.worldbank.org)	Renewable energy consumption (% of total final energy consumption)
Energy consumption	EC	World Development Indicators (https://data.worldbank.org)	Energy consumption measured by (kg of oil equivalent)
Economic growth	GDP	World Development Indicators (https://data.worldbank.org)	Gross domestic product constant 2015 US $
Population	POPU	World Development Indicators (https://data.worldbank.org)	Total population

Cooperation Council (GCC) nations. Building upon the works of Zmami et al. (2020), Shaheen et al. (2022), and others, the STIRPAT model has been widely utilized in prior research to investigate factors influencing environmental degradation in various contexts [30, 31]. As highlighted in Ref. [32], Additional variables can be integrated into the foundational STIRPAT model, expanding its components related to technology (T). Since T signifies the environmental impact per unit of economic activity, this research has subdivided it into two constituents that capture variations in each country's economic structure regarding energy sources: renewable energy and non-renewable energy (coal, oil, and natural gas consumption). Consequently, T is further categorized into renewable and non-renewable energy utilization. See equation (1), which show the formulation of the STIRPAT model form:

$$I_{it} = \beta_0 P_{it}^{\beta 1} A_{it}^{\beta 2} T_{it}^{\beta 3} \omega_{it} \tag{1}$$

where P is the population size (represented by total population), A stands for the real GDP, T stands for the technology represented by renewable and non-renewable (oil, natural gas, and coal) energy consumption, i and t denote the year and country, and ω represent the error term. Once the natural logarithm of all the variables has been computed, and adding the variables that considered one of the most important influences on the environment, See equations (2) and (3), which show the model final form:

$$\mathrm{CO2} = (\mathrm{CCit}, \mathrm{OCit}, \mathrm{NGCit}, \mathrm{REit}, \mathrm{ECit}, \mathrm{GDPit}, \mathrm{POPUit}) \tag{2}$$

$$lnCO_{2\ it} = \beta_0 + \beta_1 lnCC_{it} + \beta_2 lnOC_{it} + \beta_3 lnNGC_{it} + \beta_4 lnRE_{it} + \beta_5 lnEC_{it} + \beta_6 lnGDP_{it} + \beta_7 lnPOPU_{it} + \omega_{it} \tag{3}$$

where CO_2, CC, OC, NGC, RE, EC, GDP, and POPU are the carbon dioxide emissions (indicator for environment degradation), coal consumption, oil consumption, natural gas consumption, renewable energy consumption, final energy consumption, economic growth, and population, respectively. where β_0 denotes a constant term based on individual cross-sections, ω_{it} is the cross-sectional residual terms, *ln* is the logarithm symbol, *i* stands for individual countries sampled for the study (i.e., $i = 1,2, \ldots, N$) and *t* signifies the time span (1995–2017). β1, β2, β3, β4, β5, β6 and β7 on the other hand captures the long-term elastic effect of the proposed determinants (CC, OC, NGC, RE, EC, GDP, *and* POPU) respectively on emission of carbon.

The association between the consumption of coal and CO_2 have been investigated by Adebayo et al. for Japan [33], Kanat et al. for Russia [34], Kartal et al. for the five leading carbon-emitting nations [35], Pata for Turkey [36], Cheng et al. for China [37], and Yuping et al. for Argentina [4]. Their findings suggest a direct correlation between the consumption of coal and CO2. As a result, this study anticipates a positive connection between CO2 and the consumption of coal. i.e., ($\beta_1 = \frac{lnCO_2}{lnCC_{it}} > 0$). The connection between oil consumption and CO_2 emission have been examined by Adebayo et al. for Japan [33], Kanat et al. for Russia [34], Kartal (2022) for the five leading carbon-emitting nations [35], Lim et al. For three nations in East Asia that import oil [38], Saboori et al. for China and Japan [39], and Yuping et al. for Argentina [4]. Their research uncovers that one of the primary contributors to CO2 emissions is oil consumption, and when oil consumption rises, carbon emissions also increase. Consistent with these findings, our study anticipates a positive association between the consumption of oil and CO2. i.e., ($\beta_2 = \frac{lnCO_2}{lnOC_{it}} > 0$). The linking between gas consumption and CO_2 emission have been explored by Adebayo et al. for Japan [33], Kanat et al. for Russia [34], Kartal (2022) for the five leading carbon-emitting nations [35], Bimanatya & Widodo (2018) for Indonesia [40], Yuping et al. (2021) for Argentina [4]. These investigations have demonstrated a significant connotation between CO2 and natural gas consumption. In contrast, Dong et al. (2018) argue that the consumption of natural gas can help reduce CO2 emissions in 14 Asia-Pacific countries [41]. Nevertheless, these studies predominantly reveal a positive correlation, although the possibility of a negative correlation cannot be ruled out. Therefore, our study anticipates the potential for either a positive or a negative connection between the consumption of natural gas and CO2. i.e., ($\beta_3 = \frac{lnCO_2}{lnNGC_{it}} > 0$) or ($\beta_3 = \frac{lnCO_2}{lnCC_{it}} < 0$).

Many studies explore the relation between the consumption of energy and CO_2 emission. Yazdi & Shakouri (2014) [42], Liu et al. (2016) [43], Bekhet et al. (2017) [44], Sarkodie (2018) [45], Adebayo & Akinsola (2020) [46], and Shan et al. (2021) [9], Studied this relationship for Iran, China, GCC countries, 18 Africa countries, MINT (Mexico, Indonesia, Nigeria, Turkey) countries, Thailand, Turkey, respectively. These studies indicate a positive relationship between CO2, energy consumption, and economic growth. They suggest that as the consumption of energy and economic growth increase, so do CO2 emissions. Taking these studies into account, we anticipate a positive association between CO2, the consumption of energy, and economic growth. i.e., ($\beta_5 = \frac{lnCO_2}{lnEC_{it}} > 0$) and ($\beta_6 = \frac{lnCO_2}{lnGDP_{it}} > 0$). The research conducted by Zafar et al. (2019) [47], Koc & Bulus (2020) [48], Sharif et al. (2020) [49], Adebayo, Udemba et al. (2021) [50], Shan et al. (2021) [9], Yuping et al. (2021) [4], and Zhan et al. (2021) [51], came to the consensus that higher adoption of renewable energy sources results in a decrease in CO2. These studies generally establish a negative association between CO2 and the utilization of renewable energy. Therefore, it is anticipated that there will be a negative association between CO2 and the consumption of renewable energy. i.e., ($\beta_4 = \frac{lnCO_2}{lnRE_{it}} < 0$). Finally, the association between population and CO_2 emission have been investigated by MENSAH (2020) for African countries [52], Sahar Shafiei [32] for OECD countries. Their results concluded that population drives CO_2 emission. Hence, in this work a positive connection is expected between population and CO_2 emission. i.e., ($\beta_7 = \frac{lnCO_2}{lnPOPU_{it}} > 0$).

3. Empirical methodology

The experimental methodology used in this work is consists of sequential steps, none of which should be ignored, see Fig. 2.

4. Descriptive statistics and correlation matrix

We will conduct preliminary statistical tests to know the characteristics of all the variables that will be used in the model analysis, among the essential characteristics of the statistical variables that will be identified (minimum, maximum, average value, standard deviation, and observations for each variable separately). We will also teste the correlation matrix for the total of GCC countries, through which we will identify the pattern of relationships among the variables under study.

4.1. Multicollinearity, heteroskedasticity, endogenous, and autocorrelation tests

As commonly understood, multicollinearity represents a statistical challenge wherein two or more predictor variables within a multiple regression model exhibit strong correlations. This implies that one of these variables can be accurately predicted using a linear relationship with the others to a significant extent. For that, we will check whether this problem exists in our statistical model or not by using Variance inflation factor (VIF) test [53]. As known that when the error term variance u does not differ with the independent variables then we are in the good road, which called Homoscedasticity. If the error term variance u varies with the independent variables, it indicates that we are in the bad road, which called the problem of heteroscedasticity. For that, we will check whether this problem exists in our statistical model or not by using Breusch-Pagan/Cook-Weisberg (BPCW) heteroskedasticity test [54,55]. Endogenous issue happens if one or more predictors variables in the equation are connected with the error term. If there is an endogeneity issue in the model, the OLS estimator is no longer a consistent estimator. We will check whether this problem exists in our statistical model or not by using Hausman (1978) Endogeneity Test (Hausman Specification Test) [56]. The autocorrelation problem means that the error term of one period is correlated with the error term of any previous periods. In other words, for this problem to be not exist, the error term of different individuals must be independent of each other in all periods. For that, we will check whether this problem exists in our statistical model or not by using Wooldridge autocorrelation test [57,58].

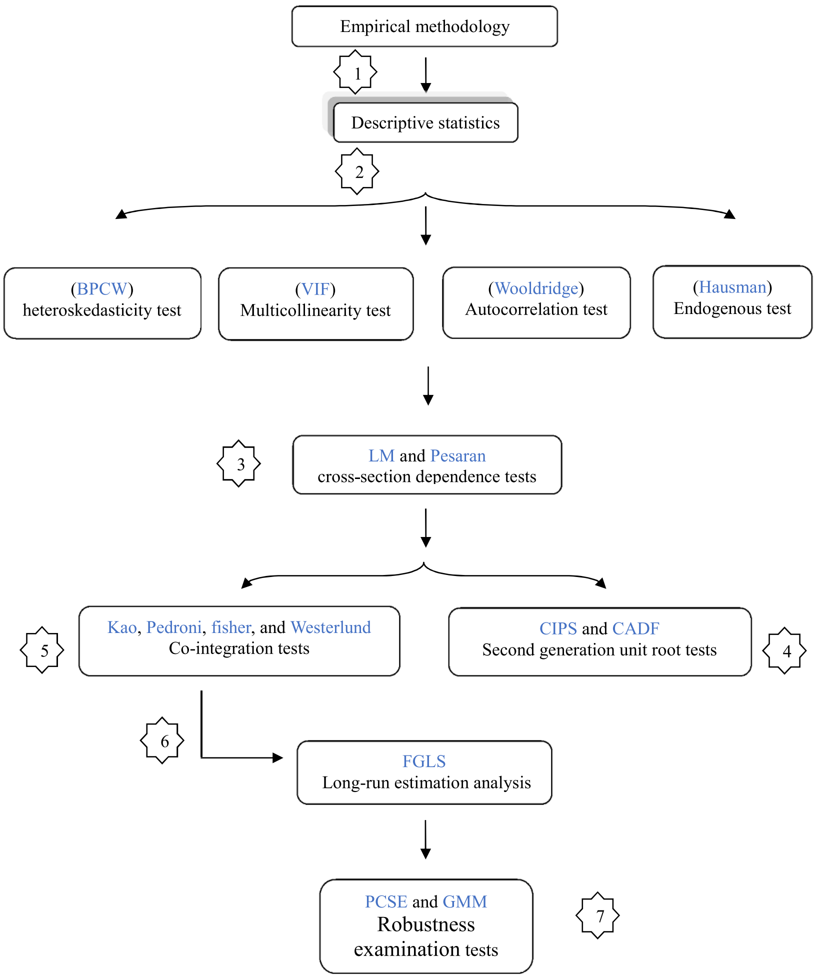

Fig. 2. Empirical methodology structure.

4.2. Panel cross-section dependence test

In this section, we apply the Lagrange Multiplier (LM) method as originally introduced by Breusch & Pagan (1980) [59], along with the Cross-section dependence (CD) test, initially proposed by Pesaran (2014) [60]. These methods are employed to assess CD in panel data. It is worth highlighting that CD may arise in cases where countries exhibit global or regional interconnectedness. Therefore, investigative CD is necessary as failing to do so may result in incorrect, biased, and contradictory results in panel data analysis [61].

Equations (4) and (5) developed by Breusch and Pagan (1980) and Pesaran (2004) can be expressed as:

$$LM = \sum_{i=1}^{N-1} ! \sum_{j=i+1}^{N} T_{ij}\widehat{\rho}_{ij}^{2} \rightarrow x^{2}\frac{N(N-1)}{2} \tag{4}$$

$$CD = \sqrt{\frac{2}{N(N-1)}} \sum_{i=1}^{N-1} ! \sum_{j=i+1}^{N} T_{ij}\widehat{\rho}_{ij} \rightarrow N(0,1) \tag{5}$$

The symbols used in these equations are as follows: $\widehat{\rho}_{ij}$ denotes the correlation coefficient, x^2 represents the asymptotic circulation for fixed cross-section size, N is the observations number, and T is the period. According to Pesaran (2004), it is recommended that T_{ij} should approach infinity first ($T_{ij} \rightarrow \infty$), followed by N approaching infinity ($N \rightarrow \infty$), in any order [60]. Pesaran explained that if $T_{ij} > k + i$ and N is sufficiently large, then the value of the common factor is equal to zero (i.e., CD = 0) for an extensive panel data range. In these tests, the null hypothesis posits the absence of a shared factor among the countries in the sample, whereas the alternative hypothesis posits the existence of a common factor.

4.3. Panel data unit root tests

Once the null hypothesis is rejected in the CD test, the next step involves evaluating the integration order for all the variables. It's important to note that the first-generation unit root tests (IPS, Im, Pesaran, LL) are not suitable for variables influenced by CD-related issues [62]. Therefore, in this study, We utilize second-generation unit root tests, specifically the cross-sectional augmented (CIPS) and cross-sectional augmented Dickey-Fuller (CADF) tests as introduced by Ref. [63]. These tests are considered more robust when dealing with heterogeneity and common factor problems among the countries under examination [64,65].

The mathematical representation of these tests statistic in equation formula can be articulated as follows, see equation (6):

$$\Delta x_{it} = \alpha_{it} + \beta_i x_{it-1} + \rho_i T + \sum_{j=1}^{N} \theta_{it}\Delta x_{i,t-j} + \varepsilon_{it} \tag{6}$$

The formula involves the use of the symbol Δ to represent a differenced function. The symbol x_{it} is used to denote the variable being analyzed, which is characterized by both time series and cross-section properties. Additionally, $x_{i,t-j}$ is introduced as a lagged first-difference term to address the issue of autocorrelation amid the errors. The symbol $\boldsymbol{\alpha}$ is used to denote the divergent intercept, while T represents time, and ε_{it} represents the error term. The CIPS and CADF tests are performed with the H_0 hypothesis stating that the variable under examination is non-stationary, and the H_1 hypothesis suggesting it is stationary.

4.4. Cointegration test

In advance to finally guesstimate the long-term liaison amid employed series in the proposed multivariate CO_2 model, it is naturally expected to examine if structural co-integration (relationship in the long run) exists among employed variables. To gauge the robustness of the study's results, we extended our analysis by incorporating co-integration tests devised by Refs. [66,67] together with Durbin-Hausman long-term affiliation test of Westerlund (2008) due to cross-sectional interdependence and heterogeneity in the econometric analysis [68]. In summary, choosing or deciding on an optimal estimation approach is crucial, thus the affirmed long-run relationship is estimated using the Feasible Generalized Least Squares (FGLS) together with Panel Corrected Standard Errors (PCSEs) estimators.

4.5. Feasible Generalized Least Squares (FGLS)

In this empirical study, to ensure the effectiveness of the ordinary least squares (OLS) method, it is necessary to assume that all errors exhibit equal variance (absence of heteroscedasticity) and are uncorrelated (lack of serial correlation), as noted by Refs. [69,70]. To address these assumptions, we adopted the FGLS model originally established by Ref. [71] as the main approach in our research. It's well-known that FGLS is a robust estimator employed to account for issues such as autocorrelation, heteroscedasticity, and CD in panel data models [72,73]. Moreover, FGLS is particularly advantageous when dealing with panel data characterized by a temporal dimension (T) exceeding or equal to the number of cross-sectional units (N) [74]. Given that our dataset spans from 1995 to 2017 and includes data from 5 different nations, the FGLS method is well-suited for our modeling purposes.

As commonly understood in Ordinary Least Squares (OLS) regression analysis, the formula employed for computing the model coefficients can be expressed as follows, see equations (7)–(9):

$$\widehat{\beta}_{OLS} = (X'X)^{-1}X'Y \tag{7}$$

$$\widehat{u}_j = (Y - Xb)_j \tag{8}$$

$$\widehat{\Omega}_{OLS} = diag\left(\widehat{u}_1^2, \widehat{u}_2^2, \dots, \widehat{u}_n^2\right) \tag{9}$$

Equation (8) denotes the residual estimates, while equation (9) characterizes the estimated variance-covariance matrix. Unlike ordinary least squares, where the true variance-covariance matrix is typically unknown, the FGLS method shares similarities with generalized least squares (GLS) by employing an estimated variance-covariance matrix. In the GLS approach, β is estimated by reducing the squared Mahala Nobis length of the residual vector. Using weighted least squares, estimate β_{FGLS1} using $\widehat{\Omega}_{OLS}$ equations can be written as following, see equations (10)–(13):

$$\widehat{\beta}_{FGLS1} = \left(X'\widehat{\Omega}_{OLS}^{-1}X\right)^{-1}X'\widehat{\Omega}_{OLS}^{-1}Y \tag{10}$$

The residuals' estimates are calculated as follows:

$$\widehat{u}_{FGLS1} = Y - X\widehat{\beta}_{FGLS1} \tag{11}$$

The covariance matrices and the final formula are derived from:

$$\widehat{\Omega}_{FGLS1} = diag\left(\widehat{u}_{FGLS1,1}^2, \widehat{u}_{FGLS1,2}^2, \dots, \widehat{u}_{FGLS1,n}^2\right) \tag{12}$$

$$\widehat{\beta}_{FGLS2} = \left(X'\widehat{\Omega}_{FGLS1}^{-1}X\right)^{-1}X'\widehat{\Omega}_{FGLS1}^{-1}Y \tag{13}$$

4.6. Robustness examination tests (PCSEs and GMM)

So as to assess the strength of our model's experimental results in this paper, we employed the PCSEs approach, as originally proposed by Ref. [75]. Given the presence of concerns related to CD, autocorrelation, and heteroscedasticity, conventional Ordinary Least Squares (OLS) estimations become inefficient, leading to biased standard errors in the OLS estimator [76]. To enhance parameter efficiency, we employed the PCSEs estimator, which simultaneously addresses issues related to autocorrelation, heteroscedasticity, and CD [77]. The PCSEs technique emerges as a viable alternative to address the previously mentioned issues associated with OLS. This estimator, known as Panel Corrected Standard Errors (PCSEs), retains OLS parameter estimations while replacing them with panel-corrected standard errors. Beck et al. (1995) have underscored the reliability of the PCSEs method in enhancing standard error efficiency [78]. The PCSEs technique employs a two-step estimation process. Firstly, data transformation is carried out to mitigate serial correlation and heteroscedasticity. Secondly, the transformed data is subjected to OLS, with standard errors adjusted to account for autocorrelation, heteroscedasticity, and CD [74].

To confirm the results that we have got from above models, we also will conduct the panel generalized method of moments (GMM) model developed by Ref. [79], where the GMM estimator in the face of arbitrary heterogeneity has the benefit of consistency [80], as the GMM method allows for solutions to homogeneity bias and can control for individual and temporal effects. Period dummies are used to account for the fact that the system GMM estimator assumes there is no current connection between the cross-sectional error components. Additionally, it requires a first-order serial correlation within the error term but does not require a second-order serial correlation. GMM estimates may become prone to overfitting the endogenous variables and potentially undermine the test's ability to identify excessive restrictions if there is an excessive number of instruments compared to the available country-level observations in the system [81]. As a rule, the number of instruments should be kept to a minimum compared to the number of nations. To reduce the number of instruments, we utilize a lag of one or two explanatory variables as instruments and then demolish them by combining them into smaller groups [82].

Table 2
The results of Descriptive statistics.

Variables	N	Mean	Std. Dev.	min	max
CO_2	115	131051.7	135990.4	18870	565190
CC	115	0.0058348	0.0170383	0	0.089137
OC	115	1.398637	1.835625	0.0585587	7.361411
NGC	115	1.188046	0.954074	0.1200388	3.933008
RE	115	0.0243668	0.0423452	0	0.1732
EC	115	145.5738	36.64744	82.84524	239.0061
GDP	115	1.89e+11	1.72e+11	2.11e+10	6.65e+11
POPU	115	7728967	9657534	515133	3.42e+07

5. Empirical results and discussions

5.1. Descriptive statistics and correlation matrix results

Table 2 outlines the summary of descriptive statistics pertaining variables employed in the study model. results show a wide range of variations amid utilized variables in the panel. comparison to all variables, POPU obtained the largest mean value of (7728967) with spread value of 9657534 whereas CC had the least mean value of (0.0058348) with a standard deviation of 0.0170383. In terms of matching the means with the standard deviations for the respective variables, it can be deduced that, no issue of overdispersion is evidenced with the exception of only natural gas consumption, energy consumption and GDP variables which had its dispersed value to be slightly (marginally) higher than its mean.

As shown in Table 3, all the variables (natural gas, oil, coal, renewable energy, economic growth, and population) are identified to have a positive linear liaison with CO_2 emissions whereas the consumption of energy identified to have a negative linear association with CO_2. In general terms, the positive correlation amid CO_2 emission and the former variables statistically means each series with emission of carbon linearly move in the positive direction graphically indicating that an increase in any of the variable undoubtedly is likely to upsurge CO_2 emission.

5.2. Multicollinearity, heteroskedasticity, endogenous, and autocorrelation results

As we see in Table 4, the result of VIF is 16.08, and this indicates, in a certain way, the presence of Multicollinearity issue between the variables of this work. As shown in Table 5, we concluded that the Breusch-Pagan/Cook-Weisberg test result (4.08) is significant (0.0435), and thus rejecting the H_0 hypothesis and accepting the H_1 hypothesis, which proves to us the presence of Heteroskedasticity problem between the variables of this work. As shown in Table 6, we concluded that the Hausman (1978) specification test result (91.85) is significant (0.0000) at the level 1 %, and thus rejecting the H_0 hypothesis and accepting the H_1 hypothesis, which proves to us the presence of Endogenous problem amid the regression of this study. Also, as shown in Table 7, we concluded that the Wooldridge test result (62.436) is significant (0.0014) at the level 1 %, and thus rejecting the H_0 hypothesis and accepting the H_1 hypothesis, which proves to us the existence of autocorrelation problem among the variables of this work.

5.3. Panel cross-section dependence results

Considering the shared geographical and socio-economic characteristics between the sampled GCC states in the analysis panels, it is not unexpected that these countries may exhibit inter-sectoral dependencies within their respective panels. Thus, relying on this assertion, three different approaches are Pesaran CD, Pesaran scaled LM, and Breusch-Pagan LM as previously stated were adopted to examine the presence or absence of residual cross-country connectedness. As shown in Table 8, the prob-values of all results are significant. In other words, the research dismisses the H_0 hypothesis regarding CD because the results are statistically significant. This demonstrates the existence of a CD issue amid the study's panels. As previously mentioned, the expectation of CD is reasonable due to the substantial social, economic, and financial interconnections among GCC countries. This outcome affirms that in a globalized world, the majority of GCC economies are interconnected, indicating that a disturbance in one economy can have a ripple effect on others [52]. Given this pre-existing knowledge, these findings necessitate the utilization of unit root tests that factor in cross-sectional interdependence. Furthermore, the subsequent stages of the research employ state-of-the-art panel data methodologies, known for their robustness and efficiency in addressing cross-country correlation issues, thereby enabling the discovery of reliable and precise empirical results [30].

5.4. Panel unit root results

Considering the presence of cross-country residual reliance, this work additionally utilized second-generation CADF and CIPS tests to investigate the order of variables integration employed in this study. As shown in Table 9, the results from the CADF and CIPS tests interestingly and as expected indicate that according to the CIPS test, all variables are stationary at the level except for CC and POPU, which are stationary at the first difference. The CADF results indicate that CO2, CC, OC, and POPU are stationary at the level, while the other variables are stationary at the first difference. Consequently, the unit root tests confirm that all the variables are integrated at I(0)

Table 3
Correlation matrix results.

Variables	$lnCO_2$	lnCC	LnOC	lnNGC	lnRE	lnEC	lnGDP	lnPOPU
$lnCO_2$	1.000							
LnCC	0.278	1.000						
LnOC	0.978	0.250	1.000					
lnNGC	0.919	0.373	0.845	1.000				
LnRE	0.277	0.665	0.285	0.409	1.000			
LnEC	−0.106	−0.152	−0.199	−0.020	−0.367	1.000		
lnGDP	0.971	0.332	0.959	0.926	0.405	−0.215	1.000	
lnPOPU	0.922	0.239	0.927	0.781	0.204	−0.360	0.889	1.000

Table 4
Multicollinearity (VIF) result.

Variables	VIF	1/VIF
LnGDP	42.46**	0.023549
lnOC	31.09**	0.032167
lnPOPU	15.38*	0.065009
lnNGC	14.68*	0.068142
LnRE	3.55	0.281689
LnEC	3.39	0.295211
LnCC	2.05	0.488541
Mean VIF	16.08	.

Notes: ***, **, and * is the significance levels at 1 %, 5 %, and 10 %, respectively.

Table 5
Heteroskedasticity test result.

B–P/C–W test	
Ho: No Heteroskedasticity (Constant variance)	
Chi 2(1) Statistics	p-value
4.08**	0.0435

Notes: ***, **, and * is the significance levels at 1 %, 5 %, and 10 %, respectively.

Table 6
Endogenous test result.

Hausman (1978) test	
Ho: no Endogenous problem	
Chi-square value	p-value
91.85***	0.0000

Table 7
Autocorrelation test result.

Wooldridge test	
Ho: no first-order autocorrelation	
Wooldridge F (1, 5) Statistics	p-value
62.436***	0.0014

Notes: ***, **, and * is the significance levels at 1 %, 5 %, and 10 %, respectively.

Table 8
CD result.

Variables	Breusch-Pagan LM	Pesaran scaled LM	Pesaran CD
$\ln CO_2$	220.0488*** (0.0000)	46.96834*** (0.0000)	14.23830*** (0.0000)
lnCC	168.7420*** (0.0000)	35.49579*** (0.0000)	12.96020*** (0.0000)
lnOC	197.1391*** (0.0000)	41.84558*** (0.0000)	14.00387*** (0. 0000)
lnNGC	206.4787*** (0.0000)	43.93397*** (0.0000)	14.36181*** (0.0000)
lnRE	(———)	(———)	(———)
LnEC	39.81792*** (0.0000)	6.667490*** (0.0000)	3.02827*** (0.0025)
lnGDP	211.2980*** (0.0000)	45.01160*** (0.0000)	14.53183*** (0.0000)
lnPOPU	214.3199*** (0.0000)	45.68731*** (0.0000)	14.63396*** (0.0000)

***, **, and * is the significance levels at 1 %, 5 %, and 10 %, respectively. The numbers in parentheses is the prob-value.

and I(1).

5.5. Cointegration results

To investigate the long-term equilibrium process, panel cointegration experiments were employed. In line with previous research [83,84], and [52], this work utilized Kao, Peroni, Fisher, and Westerlund cointegration tests. The outcomes of these tests, presented in

Table 9
The result of Unit root tests.

variables	CIPS test		Integration Order	CADF test		Integration Order
	Level	First difference		Level	First difference	
$lnCO_2$	−2.109	−4.130***	I(1)	−2.410* (0.067)	–	I(0)
lnCC	−4.292***	–	I(0)	−2.481** (0.048)	–	I(0)
lnOC	−2.188	−3.191***	I(1)	−2.834*** (0.007)	–	I(0)
lnNGC	−2.162	−4.288***	I(1)	−1.643 (0.606)	−2.842*** (0.006)	I(1)
lnRE	−2.029	−3.719***	I(1)	−1.697 (0.558)	−2.860*** (0.006)	I(1)
lnEC	−1.700	−3.168***	I(1)	−1.976 (0.309)	−3.092*** (0.001)	I(1)
lnGDP	−1.802	−3.097***	I(1)	−1.879 (0.392)	−2.327* (0.096)	I(1)
lnPOPU	−3.572***	–	I(0)	−4.135*** (0.000)	–	I(0)

***, **, and * is the significance levels at 1 %, 5 %, and 10 %, respectively. The numbers in parentheses is the prob-value.

Table 10, offer strong evidence for rejecting the H_1 hypothesis of no cointegration. The group and panel statistics, along with their respective robust prob-values, all exhibit statistical significance, with the exception of the Westerlund test result. Thus, it can be reasonably concluded, with substantial support, that the variables under examination exhibit long-term connections that warrant further exploration.

5.6. *Feasible Generalized Least Squares results*

Given the presence of CD and concerns related to the expansion of data in the panel dataset, as demonstrated in Table 8, the analysis employed the FGLS estimator which is highly effective in solving the aforementioned problems as already stated. The regression results therefore for the whole sample are shown in Table 11. Findings from table based on the FGLS estimation technique provides the Wald Chi-square statistics for panel assessed CO_2 model are large (22464.49) and significant (0.0000). This implies that the proposed panel CO2 model represents a robust and valid specification capable of delivering accurate predictive results.

Table 11 illustrates that the coefficient linked to CC is positive but lacks statistical significance, indicating that the growth in coal consumption has coincided with environmental deterioration. This result aligns with numerous previous studies [33,35], and [34]. Undoubtedly, the effect of OC is undeniably positive and holds statistical significance at the 1 % level, indicating that 0.3304 % rise in environmental degradation (upsurge in CO_2 emissions) is related to oil consumption in GCC when all other variables are upheld continuously. This result line up with the studies [36,85], and [86]. NGC appears to have a detrimental impact on the environment in GCC nations, with a relatively high and statistically significant coefficient of 1 %. Notably, a 1 % rise in natural gas consumption, corresponds to a 0.2473 % increase in CO2 emissions. These findings align with numerous prior studies (Liu et al., 2016 [43]; Sarkodie, 2018 [45]), but contrast with others [3,41]. In the context of GCC, the coefficient associated with the dependent variable, CO2 emissions, displays a significant positive impact with respect to the independent variables of fossil fuel consumption and economic growth. This indicates that environmental deterioration is linked to the increased energy consumption accompanying GCC's rapid

Table 10
The results of Cointegration tests.

Kao test				
	Statistic		p-value	
Modified D-F t	−1.6965**		0.0449	
D-F t	−1.6751**		0.0470	
Augmented D- t	−1.1919		0.1166	
Unadjusted modified D- t	−2.1347**		0.0164	
Unadjusted D-F t	−1.8512**		0.0321	
Pedroni test				
Modified P–P t	2.4532***		0.0071	
P–P t	−2.5037***		0.0061	
Augmented D-F t	−2.7389***		0.0031	
Westerlund test				
Variance ratio	−1.0242		0.1529	
Johansen fisher panel cointegration test				
	From trace test	p-value	From max test	p-value
None	0.000	1.0000	0.000	1.0000
At most 1	0.000	1.0000	0.000	1.0000
At most 2	249.7***	0.0000	136.1***	0.0000
At most 3	214.1***	0.0000	166.9***	0.0000
At most4	171.2***	0.0000	95.18***	0.0000
At most5	106.2***	0.0000	62.47***	0.0000
At most6	62.62***	0.0000	39.99***	0.0000
At most7	45.13***	0.0000	45.13***	0.0000

***, **, and * is the significance levels at 1 %, 5 %, and 10 %, respectively. The numbers in parentheses is the prob-value.

Table 11
Feasible Generalized Least Squares results.

Variables	Coefficients	Std. Err	Z-Statistics
lnCC	0.2562 (0.625)	0.5241	0.49
lnOC	0.3304*** (0.000)	0.0263	12.57
lnNGC	0.2473*** (0.000)	0.0272	9.10
lnRE	−0.5087* (0.072)	0.2830	−1.80
lnEC	0.3289*** (0.000)	0.0433	7.59
lnGDP	0.1388*** (0.001)	0.0419	3.31
lnPOPU	0.1763*** (0.000)	0.0212	8.32
_cons	3.6944*** (0.006)	1.3363	2.76
Obs N = 115			
groups N = 5			
Time = 23			
Wald (7) = 22464.49			
P > chi2 = 0.0000			

Notes: ***, **, and * is the significance levels at 1 %, 5 %, and 10 %, respectively. The number in parentheses is the prob-value.

economic expansion. The outcome approves that natural gas, oil, and coal consumption have a positive relation to CO_2, this indicates that the utilization of fossil fuels has the potential to harm and possibly devastate a pristine environment [34]. According to FGLS results, CC, OC, and NGC emerge as key contributors to CO2 emissions. Among the three fossil fuel sources, oil consumption standing out as the foremost driver of environmental harm when compared to alternative sources, and this is agreed to our expectations, as we expected oil to be the most contributor to environmental degradation, because oil is the most widely used fossil fuel in the GCC countries during the study period. See Fig. 3, which illustrates the trend in non-renewable energy consumption in the world and GCC countries. Also, Fig. 4, which shows the amount of CO2 emissions of the GCC, measured in kilotons. Saudi Arabia has the highest level of CO2 emissions among the GCC countries, followed by the United Arab Emirates, Kuwait, Qatar, Oman, and finally Bahrain, which It has the lowest amount of CO2 emissions among the GCC countries.

Regarding RE, the research revealed a notable inverse relationship amid the utilization of renewable energy and CO2. Consequently, for every 1 % surge in RE, there was a corresponding decrease of 0.5087 % in CO2. These findings align with our initial hypotheses and are congruent with a multitude of prior studies [61,87,88]. Likewise, The FGLS findings also indicate a noteworthy significant influence of energy use on CO2. To put it differently, an increase in energy consumption is related with a 0.3289 percent rise in carbon pollution at the 1 % confidence level. Thus, there is substantial evidence of a tangible impact of energy utilization on CO2. The outcomes for CC, OC, NGC, RE, and EC align with theoretical expectations, indicating that renewable energy is beneficial for environmental quality while non-renewable energy contributes to environmental degradation [89]. These findings are unsurprising given that the GCC heavily relies on non-renewable energy sources for economic growth while utilizing less renewable energy. UAE, Kuwait, and Bahrain's usage of fossil fuels as a percentage of total energy consumption in 2017 was 91.51 %, 95.33 %, and 98.40 %, respectively, whereas it was nearly 100 % in the other nations. These nations should intensify their efforts to look for alternative energy sources like wind energy, water energy, and solar energy because energy consumption is unavoidable and essential for production and development in many spheres of life and is recognized as a significant factor in environmental degradation and an rise in CO_2 emissions [87,90,91]. We argue that the predominant use of fossil fuels, due to their abundance, rather than the utilization of renewable energy sources, is the primary factor contributing to environmental degradation in GCC economies. This finding aligns with previous research

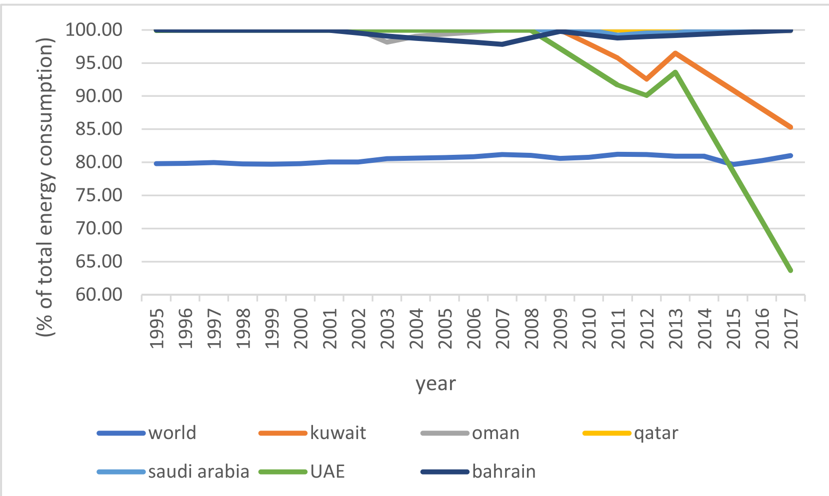

Fig. 3. fossil fuel consumption in GCC countries and world 1995–2017. Data source: World Bank.

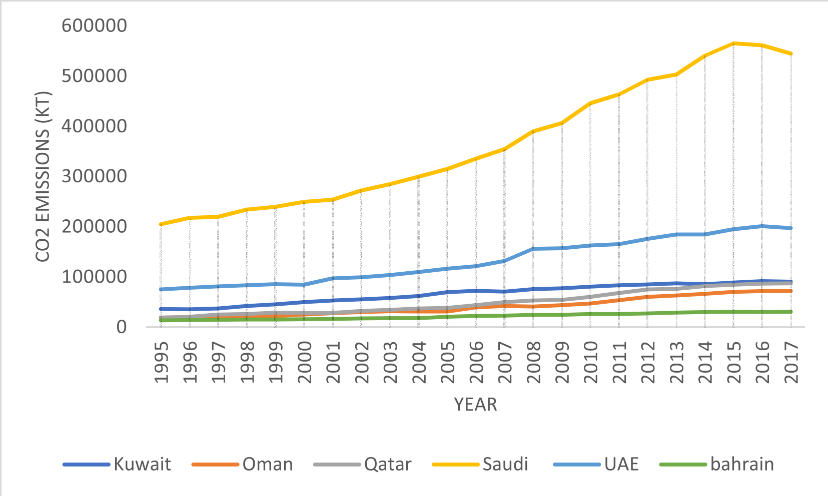

Fig. 4. CO2 emissions in GCC countries 1995–2017 (kiloton kt). Data source: World Bank.

that emphasizes the adverse impact of energy consumption on the environment in GCC nations [30,92].

There exists a substantial and positive association between GDP and CO2, with a 1 % significance level. In this context, assuming all other factors remain constant, a 1 % rise in the growth of the GCC economy is projected to lead to a 0.1388 % rise in CO2. This observation aligns with prior research, underscoring economic growth as a significant driving factor behind CO2 in GCC nations. The favorable effect of economic growth on CO2 can be attributed to the rapid economic expansion experienced by GCC countries over the past two decades. This increased income has fostered heightened economic activities, encompassing industrialization and heightened resource utilization across all sectors, consequently contributing to elevated CO2 levels and environmental degradation [61]. The increase in CO2 emissions, driven by factors such as rising income and shifts in consumption patterns from low-emission products to more energy-intensive goods and from traditional agricultural-based industries to emission-intensive sectors in the economic structure, is indicative. Consequently, as economic growth spreads across the GCC population, the lifestyles of both urban and rural residents evolve, leading to changes in consumer behavior and preferences. Ultimately, the resulting effect is the increase in CO_2 emissions. The outcomes are constant with the outcomes of many previous studies [93–96], while differing with some studies [97,98].

Finally, Population and CO_2 have a significant positive connection for the GCC nations through the study period. Hence, a 1 percent rise in the population corresponds to a 0.1763 % increase in CO2, with significance at the 1 % level. This outcome aligns with the results reported in various previous studies [30,99], which revealed a favorable connection between population size and CO2 emissions. These findings align with the theoretical predictions, which propose that a growth in population leads to a corresponding increase in energy extraction and usage for industrial production, ultimately contributing to an upsurge in CO2 emissions.

See Fig. 5, which represent the relationship results of the independent variables (natural gas consumption, coal consumption, oil consumption, renewable energy, final energy consumption, economic growth, and population) with the dependent variable (CO_2 emissions) in the GCC nations throughout the study period.

Our empirical assessment shows the ranking of the main fossil fuel contributors to environmental degradation (increased CO_2 emission) in the GCC nations, and they are gradually from the largest to the smallest contribution, oil consumption (in the first rank), coal consumption (in the second rank), natural gas consumption (in the third rank), population (in the fourth rank), and economic growth (in last rank), while it did not find any contribution to renewable energy in increasing CO_2 emissions, but it was found to enhance environmental quality. See Fig. 6, which shows the order of contributors to increase CO_2 emissions and the value of the contribution of each variable in the GCC countries.

6. Robustness examination results (PCSEs and GMM)

Analogously, the PCSEs estimator holds equal significance to the FGLS model, as it simultaneously addresses issues related to autocorrelation, heteroscedasticity, and CD [65,77]. Table 12 clearly demonstrates that the outcomes generated by the PCSEs model, employed as a robustness check in this study, align with the results obtained from the primary FGLS model. The table reveals that, over the long term, all variables, including coal consumption, oil consumption, natural gas consumption, final energy consumption, economic growth, and population, exert a positive and statistically significant influence on CO2 emissions. Conversely, among these variables, renewable energy stands out as the sole factor with a significantly negative impact on CO2 emissions.

Table 13 also shows the results of the PGMM Robustness examination test, which show complete agreement and harmony with the results of previous models (FGLS and PCSEs), every variable examined in the study, including natural gas, oil, coal, final energy consumption, economic growth, and population, exhibits a significant positive connection with CO2. Conversely, the only variable showing a significantly negative connotation with CO2 is renewable energy.

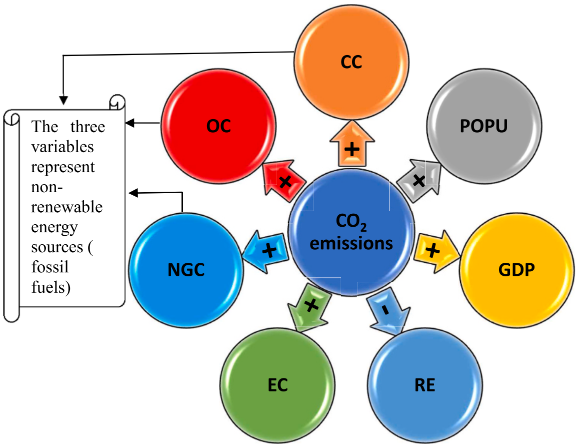

Fig. 5. The relationship results between the independent variables and CO_2.
Source: Researcher design using the results of FGLS.

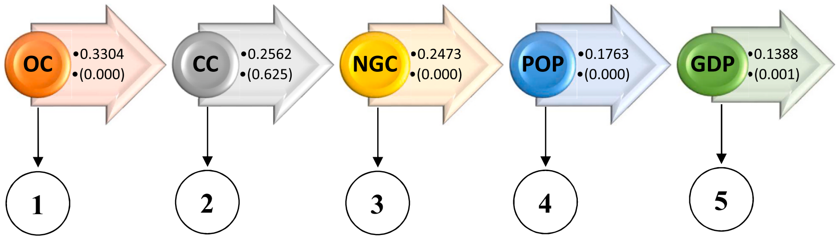

Fig. 6. The fossil fuel contributors rank to increase CO_2 emissions in the GCC countries.
Source: Researcher design using the results of FGLS.

Table 12
Panels Corrected Standard Errors (PCSEs) results.

Variables	Coefficients	Std. Err	Z-Statistics
LnCC	0.2562 (0.366)	0.2835	0.90
LnOC	0.3304*** (0.000)	0.0264	12.51
LnNGC	0.2473*** (0.000)	0.0280	8.83
LnRE	−0.5087** (0.038)	0.2446	−2.08
LnEC	0.3289*** (0.000)	0.0426	7.72
LnGDP	0.1388*** (0.004)	0.0481	2.89
LnPOPU	0.1763*** (0.000)	0.0168	10.50
_cons	3.6944** (0.012)	1.4728	2.51
Obs N = 115			
groups N = 5			
Time = 23			
Wald (7) = 27151.44			
P > chi2 = 0.0000			
R-squared = 0.9949			

***, **, and * is the significance levels at 1 %, 5 %, and 10 %, respectively. The numbers in parentheses is the prob-value.

7. Conclusion, policy implications

Exaggeration in the consumption of energy of all kinds to achieve economic prosperity was accompanied by severe environmental consequences in the GCC countries because the CO_2 emission determinants related to energy of the GCC economies are much less known. The investigation of the determinants of carbon emissions related to energy is necessary for decision makers in various countries. Consequently, this study examined the major variables causing environmental degradation (CO_2 emissions) under dis-aggregated energy consumption. To achieve the research objective, the study utilized a panel model that accounts for the impact of environmental degradation, specifically CO_2 emissions, on GCC countries from 1995 to 2017. The study used reliable and effective panel econometric techniques to avoid inaccurate results, which previous studies often overlook. The research outcomes obtained through the application of recently developed econometric techniques reveal a substantial contribution of coal, oil, and natural gas

Table 13
Panel Generalized Method of Moments results.

Variable	Coefficient	Std. Error	t-Statistic	Prob.
LnCC	0.2562	0.5433	0.4716	0.6382
LnOC	0.3304***	0.0272	12.1296	0.0000
LnNGC	0.2473***	0.0282	8.7806	0.0000
LnRE	−0.5087*	0.2934	−1.7337	0.0859
LnEC	0.3289***	0.0449	7.3230	0.0000
LnGDP	0.1388***	0.0434	3.1966	0.0018
LnPOPU	0.1763***	0.0220	8.0279	0.0000
C	3.6944***	1.3854	2.6667	0.0088
Obs N = 115				
groups N = 5				
Time = 23				
R-squared = 0.994907				
Adjusted R-squared = 0.994574				
Sum squared resid = 0.474381				
Durbin-Watson stat = 0.342128				

Notes: ***, **, and * represent the significance levels at 1 %, 5 %, and 10 %, respectively.

consumption in GCC countries to the rise in CO2 emissions. This underscores the interconnectedness of energy consumption and CO2 emissions, wherein an upsurge in energy consumption results in heightened CO2 emissions, while an increase in CO2 emissions signifies greater energy consumption. Hence, the primary policy recommendation is to decrease the utilization of fossil fuels and boost the adoption of renewable energy sources to mitigate greenhouse gas emissions and foster sustainable development. The following policy suggestions are proposed:

First, GCC nations should prioritize the formulation and implementation of policies aimed at fostering the adoption of renewable energy options such as solar, wind, and hydropower. This can be achieved through incentives like tax breaks and subsidies to stimulate investments in renewable energy technologies.

Second, The GCC countries should promote energy-efficient practices and technologies to reduce energy consumption and promote sustainable development. This can include implementing building codes that require energy-efficient buildings, promoting the use of LED lighting, hybrid cars, and other energy-efficient measures.

Third, Governments should invest in public transportation infrastructure such as trains, buses, and trams and promote their use through incentives and campaigns. This can help reduce the reliance on personal vehicles and decrease emissions from transportation.

Fourth, implementing a carbon tax or cap-and-trade system can help decrease emissions from fossil fuels by creating a financial incentive to decrease emissions. The revenue generated can be used to invest in renewable energy technologies and energy-efficient practices. also, investing in carbon capture and storage technologies has the potential to significantly decrease emissions stemming from fossil fuels. Additionally, policymakers can explore a highly efficient alternative by optimizing energy consumption, shifting towards cleaner energy sources like natural gas and hydropower, among others. Moreover, it's crucial for the governments of GCC countries to prioritize the establishment of projects aimed at ensuring an ample supply of renewable energy. This is because to minimize CO2 emittances, an upsurge in energy generation from renewable resources is required.

Finally, the research findings have revealed a positive correlation between population growth and CO2 emissions. This highlights the need for decision-makers to prioritize the implementation of policies that promote sustainable development. One such policy recommendation is the implementation of family planning programs to manage population growth effectively. By providing access to reproductive health services and education, these programs can help stabilize population growth and reduce the strain on resources and the environment. Additionally, decision-makers should focus on urban planning policies that promote sustainable transportation options and land use. This encompasses the establishment of efficient public transit systems, the creation of pedestrian-friendly urban environments, and the promotion of biking or electric vehicle usage. By embedding sustainable principles within urban planning frameworks, decision-makers can mitigate the environmental ramifications of rapid urbanization, fostering a greener and more sustainable future.

8. Future research direction

The study focused on GCC countries only, which may affect the generalizability of the findings to other regions and countries. Future research should consider expanding the scope to include multiple countries with a larger dataset or utilize a mixed-method approach to discover the phenomenon more precisely. By continuing to investigate and understand the determinants of CO2 emissions, decision-makers can make informed choices and develop effective strategies to address environmental degradation and promote sustainable development. However, it's essential to acknowledge the limitation of focusing solely on GCC countries and consider broader geographical and contextual factors in future studies to ensure a comprehensive understanding of the relationship between economic growth, energy consumption, and environmental degradation.

Data availability statement

Data will be provided upon request.

CRediT authorship contribution statement

Ebrahim Abbas Abdullah Abbas Amer: Writing – original draft, Methodology, Formal analysis, Conceptualization. **Ebrahim Mohammed Ali Meyad:** Writing – review & editing, Resources, Formal analysis. **Ali M. Meyad:** Writing – review & editing, Software, Resources. **A.K.M. Mohsin:** Writing – review & editing, Writing – original draft, Methodology, Data curation.

Declaration of competing interest

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

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Not available.

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