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Decarbonizing the Gulf: Evidence on the Role of Energy Transition, Technological Progress, and Human Capital in Achieving SDG-Aligned Sustainability

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ABSTRACT

The energy transition, green growth, technological advancements, and human capital can collectively significantly alleviate carbon dioxide emissions (CO_2e) and support long-term sustainable environmental practices. 2030 has been set as the target year by the United Nations for achieving the Sustainable Development Goals (SDGs). As the assessment period approaches, it is essential to understand the progress made by the Gulf Cooperation Council (GCC), given its significant reliance on hydrocarbons. Employing a cross-sectional autoregressive distributed lag (CSARDL) approach, this research investigates the roles of energy transition, green growth, technological innovations, human capital, economic growth, and CO_2e in the GCC, utilizing data from 1990 to 2022. The outcomes exhibit that renewable energy, green growth, technological innovations, and human capital significantly contribute to safeguarding the environment in the GCC. On the other hand, nonrenewable energy sources can harm the environment. Regarding policy implications, this research emphasizes the importance of expediting green technological innovations in GCC regions through regulatory measures that promote continuous increases in the implementation of advanced technologies, sustainable energy utilization, and the enhancement of human capital to achieve the SDGs.

Keywords: Energy Transition, Technological Innovation, Green Growth, Human Capital, Carbon Emissions, GCC Economies
JEL Classifications: J24, Q2, Q3, Q55, Q56

1. INTRODUCTION

The GCC economies, Oman, Saudi Arabia, the United Arab Emirates (UAE), Qatar, Kuwait, and Bahrain, have set a national goal to achieve carbon neutrality by 2060. The GCC nations on the Arabian Peninsula in Southwest Asia are affluent, oil-exporting emerging countries characterized by very high human development indices (AlNemer et al., 2023; Salem et al., 2023). The GCC nations own approximately 40% of global oil reserves and nearly 25% of their natural gas reserves. Furthermore, Luomi et al. (2021) found that the GCC countries' fast economic development was made possible by the revenues they gained from oil and gas exports, which in turn led to reasonable living standards for the people living in those countries. The collective economic progress of the GCC, measured by purchasing power parity, currently surpasses that of the BRICS countries. Consequently, during rapid industrialization, the GCC regions remain influential economies worldwide. The rapid GDP growth of these panel countries,

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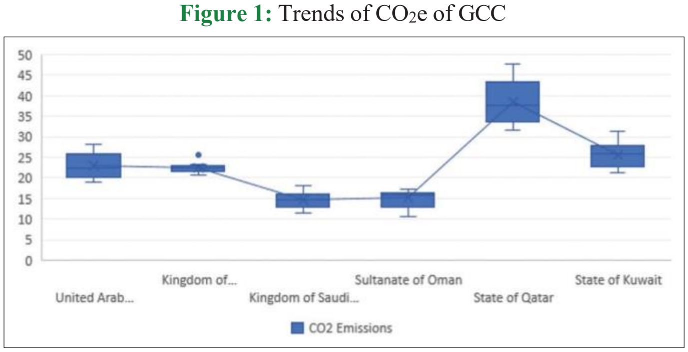
coupled with their considerable population increase, necessitates an escalation in energy consumption. These economies account for 42% of global energy use and bear a significant responsibility for CO_2e (Wang et al., 2025). In this context, the GCC countries accounted for 43% of global CO_2e in 2020, indicating significant contributors to global emissions, with Kuwait, Qatar, and the UAE being the leading carbon-emitting economies (Figure 1). The escalating CO_{2e} in the area is attributed to various nations' increased exploration and utilization of the region's abundant fossil fuel resources. According to Alharbi and Csala (2021) and WDI (2021), the increased CO_2e from energy utilization in the transport and manufacturing sectors contributes to atmospheric pollution, intensifying weather-related issues, such as high temperatures and flooding.

In light of rising emissions, governments must adopt a Green Growth (GG) strategy to mitigate environmental deterioration significantly (Choudhury et al., 2023; Zhou et al., 2022). GG, characterized as more climate-friendly growth, is often considered an essential approach for accomplishing the SDGs, mitigating poverty, promoting socioeconomic progress, enhancing social security, and effectively tackling challenges associated with resource distribution and environmental degradation (Dogan et al., 2022). GG seeks to achieve social sustainability by emphasizing ecological conservation through environmental protection, sustainable production, and the use of green technology (Cao et al., 2022; Amin et al., 2025) GG denotes an economic growth plan that safeguards scarce natural resources, enhances human well-being, and achieves sustainability while mitigating adverse environmental impacts. In alignment with the global "going green" initiative, the GCC countries are implementing measures to achieve an environmentally sustainable economy (Magazzino, 2023; Shang et al., 2023; Cao et al., 2022; Lin and Zhou, 2022; Merino-Saum et al., 2020). As a result of the widespread promotion of the concept of green growth, individuals and organizations are rapidly implementing transformation and upgrade plans in line with government policies, reducing their dependence on traditional sources, and increasing their investment in sustainable technology. Businesses can be confident that the financial sector will provide sufficient resources to help them maximize and modernize their operations, opening the path for a green economy (Lin and Zhou, 2022). The continuous expansion of sustainable financing allows banks to support companies that significantly defend the environment, reallocating resources from businesses with high carbon emissions to those with low carbon emissions.

Figure 1: Trends of CO_2e of GCC



Sources: (British Petroleum, 2020)

This, in turn, helps slow down environmental degradation in the GCC regions. Nonetheless, GCCs are regarded as the foremost carbon-emitting economies, and their cumulative effect on global warming might be substantial (Amin et al., 2024). Consequently, the study's findings may provide appropriate strategies to enhance the long-term sustainability of the GCC countries.

Countries globally are confronting the dual crises of global warming and atmospheric alteration due to the substantial growth in greenhouse gas emissions (GHGe) in recent decades (Shang and Luo, 2021; Zhao et al., 2023). There is a growing interest in how technological innovations (TI) enhance sustainability in response to escalating concerns over environmental quality. By adopting innovative technology, nations may advance economic development while safeguarding the environment (Ghosh et al., 2022). The GCC economies are among the fastest-growing regions worldwide; nonetheless, they face significant ecological challenges, with Qatar identified as the leading CO_2 emitter. The adoption of TI in these the GCCs substantially reduces environmental pollution, promotes sustainability, and lessens the adverse impacts of global warming. Moreover, TI is sometimes seen as contingent upon the extent of investment in R&D (Amin et al., 2025); hence, fostering R&D will assist the GCCs in achieving their carbon reduction objectives. Advancing sustainability and alleviating adverse environmental effects are two essential roles of innovative technology in attaining environmental sustainability. Zheng et al. (2023) assert that traditional energy sources, particularly fossil fuels, have intensified ecological challenges, including climate change and air pollution. In contrast, innovative technologies seek to enhance sustainability while concurrently mitigating the detrimental environmental impacts of economic activities (Fan et al., 2024). Technological developments include many sustainable solutions, such as RE sources, fuel-efficient machinery, and resilient transportation networks. These technologies can mitigate CO_2e and alleviate other adverse environmental impacts associated with the growth process (Saqib and Usman, 2023). The GCC countries must enact laws to encourage the use of eco-friendly technologies. For example, they must establish standards and regulations that support the use of green manufacturing methods, ultimately boosting R&D to enable businesses to benefit from sustainable applications. Additionally, novel technologies may open up new prospects of economic development and employment. For instance, the RE industry has experienced remarkable growth in recent decades, generating new employment opportunities and possibilities in fields such as solar panel production, wind turbine construction, and sustainable farming (Amin et al., 2025).

Mitigating global warming necessitates substantial reductions in GHGe throughout the next decades. One of the critical issues is how the GCC economies might reduce its emissions or, alternatively, what variables affect GHGe. A substantial fraction of the GCC's energy generation, cement manufacture, and other industrial activities depend on coal, leading to enormous CO_2e into the environment. Consequently, transitioning from non-renewable energy (NRE) to renewable energy (RE) sources, such as biomass, marine, and hydro energy, has surfaced as a viable alternative to promote sustainability and mitigate adverse environmental consequences (Sarkodie et al., 2020; Amin et al., 2024). RE sources provide electricity without contributing to pollution from fossil fuels, thereby mitigating the severity of climate change and reducing environmental degradation by replacing conventional energy sources with renewable ones. Doing so can help reduce global warming and promote environmental protection. Moreover, implementing clean energy technology may open up new avenues for employment development and economic expansion (Hao et al., 2021), ultimately facilitating the achievement of the SDGs while concurrently mitigating the adverse ecological effects. The use of clean energy is essential for a sustainable future. In this regard, measures connected with RE deployment can substantially reduce environmental pollution in GCC regions. Moreover, these economies must adopt legislative agendas that include tax incentives and subsidies to invest in RE sources.

In addition, human capital (HC) indicates the skills, competencies, and knowledge that can be advanced through training and education. People who are more educated and skilled are more likely to recycle, use public transportation, and engage in other environmentally friendly behaviors (Feng et al., 2024). Additionally, they are more inclined to promote sustainable development approaches and support environmental regulations. Moreover, people with technical competencies can implement innovative technologies, including energy-saving structures and solar energy systems. From a policy perspective, the initiatives should enhance the development of HC. This can be achieved through educational initiatives emphasizing ecological sustainability and eco-friendly environmental practices. Governments should capitalize on skill enhancement initiatives and professional education to train the labor force with the basic expertise to support sustainability (Sarkodie et al., 2020). Moreover, GCC regions may collaborate on environmental measures and optimize performance sharing to tackle common challenges. This may include information sharing platforms, collaborative research initiatives, and policy guidance to address environmental challenges. This collaboration may enhance and impact the resources and capabilities of each nation, promote innovation, and expedite the transfer of technology for sustainable development. The GCC regions may mitigate environmental pollution by addressing policy-level issues while promoting clean energy, technological innovation, green growth, and human capital progress.

This study addresses the following research questions.

1. Do RE and NRE influence CO_2e in the GCC regions?
2. Does GG mitigate emissions?
3. Does TI contribute to improving environmental quality?
4. Does HC reduce environmental deterioration?

The primary contribution of this study can be expressed in several ways, thereby significantly contributing to environmental sustainability in the GCC countries. First, this research aims to provide a novel approach to the ecological nexus in the GCC regions by leveraging RE, NRE, TI, GG, and HC. The use of conventional energy sources, however, may cause significant ecological concerns. Hence, to reduce CO_2e and foster economic sustainability, it is necessary to adopt green energy sources, innovative technologies, promote green growth, and human capital. The governments in GCC regions may utilize these traits to enhance their environmental regulations and develop more effective environmental policies. Second, this research examined RE and NRE to explore the factors significantly affecting CO_2e. A thorough analysis is necessary to bridge the research gap and assess the impact of energy diversity on environmental sustainability by examining the economic systems of the GCC economies. Furthermore, these nations' export and manufacturing sectors are highly competitive, heavily relying on industrial expertise. In recent decades, the GCC countries have committed to cleaner energy in response to global pressure and their desire to meet the objective of carbon neutrality. Third, GG is vital for achieving sustainable development as it fosters economic advancement while mitigating environmental harm. In the present study, GG helps fill the gap by satisfying the demands for economic models that include environmental protection. Accordingly, this research aims to determine whether environmentally adjusted multifactor productivity growth helps maintain high CO_2e levels in this region. Fourth, this study accounts for potential heterogeneity and cross-sectional dependence (CSD) to obtain consistent and unbiased estimates. Such a study is relevant and valuable at a time when cleaner energy sources and environmental sustainability are priorities for the GCC regions. Fifth, since the COVID-19 pandemic, the GCC's reliance on fossil fuels for power generation, transportation, and industry has increased regional CO_2e. Achieving carbon neutrality has become a national goal for countries worldwide; however, the GCC economies are unclear about how to address future climate change legislation. It is crucial to offer comprehensive policy recommendations in light of the global nature of climate change. Given the urgency of climate change as a global issue, this research makes substantial contributions to international environmental governance. Moreover, nations under significant pressure to reduce CO_2e may implement targeted strategies to promote clean energy development by using insights from the GCC's experience.

The subsequent parts are organized as follows. The second section comprises a literature review. Section 3 discusses the theoretical background. Section 4 illustrates the data, model, and methodology. Section 5 presents results and discussions. Section 6 discusses the conclusion, essential policy recommendations, and limitations.

2. LITERATURE REVIEW

Ecological risks stem from harmful emissions, particularly CO_2e, primarily contributing to this issue. The progression and development of novel technologies, combined with the utilization of RE sources, contribute to decreasing the adverse ecological impact of CO_2e on the environment. This section discusses the existing research examining the association amongst CO_2e, RE, NRE, GG, TI, and HC.

Transition to green energy is necessary for stimulating development and enhancing ecological sustainability (Adebayo et al., 2023; Saidi and Omri, 2020). RE sources are naturally occurring methods for meeting residential energy needs. Numerous researchers have demonstrated the adverse consequences of unsustainable energy on the ecosystem; researchers are now interested in studying the correlation between RE and CO_2e. For instance, Solarin and Al-Mulali (2018) utilized a second-generation estimation technique to compare 20 advanced economies. They concluded that real per capita income and RE are the primary factors influencing environmental pollution. Moreover, Fakher (2019) found that population, economic development, and green energy significantly influenced CO_2e in petroleum-producing nations from 1996 to 2016. The examined data reveal that economic growth, a growing population, and unsustainable energy sources contribute to the EFP, while RE substantially reduces it. Nathaniel et al. (2021) analyzed the interconnections among the BRICS countries regarding EFP, HC, and RE. Their research demonstrated that RE mitigates EFP, whereas the exploitation of natural resources and GDP growth augments it. Moreover, recent studies have underscored the crucial significance of RE in mitigating pollution (Usman et al., 2023; Saqib and Usman, 2023). Prior research has shown that RE has successfully reduced CO_2e in several countries, including Morocco (Khan et al., 2022), South Korea and Germany (Maennel and Kim, 2018), the US (Jeon, 2022), and China (Zhang and Zhang, 2021; Long et al., 2015). Nevertheless, the researchers could not distinguish between the effects of RE production and consumption on CO_2e. One of the advantages of producing energy from green sources is the reduction in the need to import fossil fuel sources. Given the extreme volatility of the costs of imported NRE sources, it is crucial to stabilize nations' macroeconomic performance by mitigating the effects of adverse shocks to petroleum prices in the global market. Accordingly, policy-makers must take practical steps regarding evaluations from both the consumption and production sides.

Environmentally friendly TI refers to novel approaches that simultaneously reduce pollution and promote economic development (Gao et al., 2022). Moreover, TI is an initiative by economies to reduce pollution levels that contribute to environmental variability. Given GCC's dependence on petroleum and other unsustainable sources to run their manufacturing activities and infrastructure, TI in these economies increases CO_2e. Data regarding green patent applications is commonly utilized to assess TI, which denotes modernization efforts to mitigate industrial operations' environmental effects (Cinar and Yilmazer, 2021; Kammerer, 2009). Previously, researchers found that TI makes the world more sustainable. For instance, Wang et al. (2023) concluded that TI tends to diminish pollution, hence fostering a cleaner ecosystem. Moreover, Lin and Ma (2022) concluded that TI may exert either an indirect or direct influence on CO_2e, depending upon factors such as population size, institutional quality, real income, education, and investment levels. Khurshid and Deng (2021) investigated the connection amongst TI and the environment by looking at various types and characteristics of green technology. Using the GMM approach, Erdogan et al. (2020) explored the association between TI and CO2e in G-20 economies from 2000 to 2014. The authors concluded that promoting R&D considerably reduces CO_2e. Ullah et al. (2021) studied the influence of green technologies on CO_2e for Pakistan. Their results show that utilizing green technologies ultimately improves environmental quality. Conversely, few researchers, for instance, Cheng et al. (2022) and Sharif et al. (2022) found that TI adversely affects CO_2e. Prior research has overlooked the short-term effects of innovation on the environment, such as higher use of fossil fuels, in favor of studying the longer-term benefits, such as cleaner technology and greater energy efficiency. Since rapid development is associated with temporary surges in CO_2e, GCC must address this gap. Studies focusing on SDGs should pay greater attention to this aspect.

Research on GG progressed after the 2008 financial crisis, with most studies concentrated on advanced countries. There is a vast body of studies on GG from both theoretical and empirical perspectives, and previous studies cover a diverse range of related topics, including technology, trade, employment, and production (UNEP, 2013; Lee and Chou, 2018). Achieving sustainability requires GG, which is crucial for economic and environmental development (Jacobs, 2012). According to Jouvet and de Perthuis (2013), GG is broadly known for its monetary value and vital importance in the growth process of underdeveloped nations. Moreover, Hao et al. (2021) stated that the benefits of GG strategies include resource productivity, integrating natural asset value into financial assessments, and considering environmental externality pricing. Amin et al. (2025) studied the correlation between GG, RE, and CO_2e in China. The study's results suggest that promoting GG and green energy correlates with a reduction in CO_2e. Consequently, the notion of GG is an essential strategy for achieving the SDGs. Numerous studies are being carried out in the area of CO_2e and ecological sustainability, which is broadening to include several environmental characteristics and how they interact with ecological and socio-economic issues. Qu et al. (2020) examined how the global value chain affected environmentally friendly development in China. In addition, the impact of environmental and political variables on explaining GG was further explored (Sohag et al., 2019). Our research focused on the inverse situation, mainly on GCC economies, the world's leading carbon emitters, and how GG influences emissions concerning other environmental variables.

From HC's perspective, Li and Xu (2021) investigated the association amongst human development (HD) and CO_2e, employing panel data from 2004 to 2017. Their findings indicated an inverted U-shaped correlation amongst HD and CO_2e in China. Abdouli and Omri (2020) conducted a study analysing the correlation among GDP, HC, and CO_2e for the Mediterranean region from 1990 to 2013. Their findings demonstrate a bidirectional causal link between GDP growth, HC, and CO_2e. Zivin and Neidell (2013) concluded that environmental contamination harms the personal well-being of specific individuals. Ecological dominance is far more harmful at the production level, as GDP growth is a metric for evaluating health and human capital. Sarwar et al. (2020) presented research from 161 countries spanning 2000 to 2016, assessing the relationships among health, education, GDP growth, and CO_2, which revealed a contradictory outcome on a broader scale. They found an insignificant correlation between HC and CO_2e. Ahmed and Wang (2019) studied the correlation between EFP and HC in India from 1971 to 2014 within a specific national context. Amin and Dogan (2021) examined the influence of technology advancements on CO_2e for China from 1990 to 2020, demonstrating that innovation was associated with utilizing HC and RE, as well as a decrease in CO_2e. This research examined the potential negative impact of HC on the total EFP. This research examined the potential negative effects of HC on the total CO_2e.

Although previous research has shed light on the specific ways in which RE, NRE, TI, GG, and HC significantly affect CO_2e, the cumulative and distributive effects of these factors still require examination, particularly in the context of the GCC. In terms of lowering emissions and encouraging the achievement of SDGs, a wide range of studies have failed to account for the combined effects of the variables. Moreover, specific policy recommendations are lacking due to the frequent neglect of the GCC nations' unique economic and environmental features. To address this gap, research is needed to compare the CO_2e of GCC countries at different levels of technological innovation, energy transition, human capital, and green growth. This research aims to address these gaps by comprehensively analyzing the synergistic effects of sustainability programs in the GCC, uncovering new insights and practical implications for achieving the SDGs. Furthermore, this research asserts that the differentiated effects of RE, NRE, GG, TI, HC, and GDP on CO_2e in the selected economies have not been comprehensively examined, particularly in relation to achieving the SDGs 7, 9, 13, 14, and 15.

3. THEORETICAL BACKGROUND

This section presents a theoretical background that explains the impact of technological and structural variations in a country. We advance our theoretical framework by using the neo-classical production function described below:

$$Z_t = A_t \{L_t K_t\} \tag{1}$$

In Equ (1), Z represents aggregate production, whereas A_t denotes the fraction of output variation attributed to variables excluding capital and labour. L_t represents human capital, while K_t denotes capital, which comprises both raw labour and human capital. According to Eriksson (2013), the generic equation for emissions is shown below:

$$Q_{it} = MQ_{it} Z_{it} \tag{2}$$

In Equ (2), the Q_{it} represents aggregate emissions from all economic sectors. The percentage of pollutions generated by the manufacturing process is represented by MQ_{it}, where Z_{it} is the production level from each sector. The pollution is contingent upon MQ_{it} Z_{it}, if MQ_{it} is inversely correlated with Q_{it}, it is considered an eco-friendly technological advancement, and as production increases, emissions decrease. The algebraic representation of the aggregate emissions is given below:

$$Q_t = Z_t \sum_{i=1}^{n} \partial_{it} MQ_{it} \tag{3}$$

Where total production from all sectors and the proportion of each industry, that is, $\partial_{it} = {Z_{it}}/{Z_t}$ in aggregate production is represented by Z_t and ∂_{it}. Furthermore, the aggregate of each industry's contribution is equivalent to one. By differentiating Equation (3) with respect to time, we get the equation shown below.

$$r^U = r^V \sum_{i=1}^{p} \phi_i r^{QU_i} + \sum_{i=1}^{p} \phi_i r^{\tau_i} \tag{4}$$

On the right-hand side of Equ (4), there are scale effect r^V, the technological effect r^{QU_i}, and the composition effect r^{τ_i}, where $\varnothing_i = {U_{it}}/{U_t}$ denotes the percentage of sector i in aggregate emission. Supposing no composition effect and a negative correlation between r^U and aggregate production, one might expect increased production to result from utilizing eco-friendly technology which further signifies a cumulative output. However, the ratio of decrease in pollution levels is larger than or equal to the increase in overall production, as indicated below:

$$r^U \leq if\, r^V \leq -r^{QU} \tag{5}$$

Alternatively, it may be expressed as below:

$$r^V = -r^{QU} + r^U \tag{6}$$

This expression illustrates how emissions-intensive sources increase the production levels, whereas technological advancements lower output. Moreover, below is the emission function that determines green growth.

$$Q = Z^a MQ^{-d} \tag{7}$$

In Equ (7), Z represents GG if it is ecologically sustainable. The remaining terms are described in Equ (2). By differentiating Equ (7) twice with respect to MQ, we can conclude that a rise in sustainable technologies may diminish the overall pollution.

$$\frac{\partial Q}{\partial MQ} = -cZ^a MQ^{-c-1} < 0 \tag{8}$$

$$\frac{\partial^2 Q}{\partial MQ^2} = c(c+1)Z^a MQ^{-c-2} > 0 \tag{9}$$

The first-order condition states that emissions decrease as TI increases. However, the second-order derivative implies that more increases in eco-friendly technology can lead to a diminishing marginal impact on emissions. The first-order and second-order derivatives for GG are represented as below:

$$\frac{\partial Q}{\partial Z} = [-]\beta Z^{\beta-1} MQ^{-c} \begin{smallmatrix} < \\ - \\ > \end{smallmatrix} 0 \tag{10}$$

$\frac{\partial Q}{\partial Z}$ must be less than zero for green growth

$$\frac{\partial^2 Q}{\partial Z^2} = d(d+1)SZ^{-\beta-2} MQ^{-c} \lesseqgtr 0 \tag{11}$$

In this context, we posit that output growth is sustainable, characterized by eco-friendly practices resulting from the enhancement of sustainable manufacturing methods. Equation (7) is expressed in logarithmic form as below:

$$lnQ(t) = \alpha \ln(Z) - dln(MQ) \quad (12)$$

Sustainable economic growth may only be attained if the following condition holds:

$$r^U \leq 0 \, if \, \alpha[g^P + s] \leq \beta \, r^{QU} \quad (13)$$

This indicates that a higher value of *β* correlates with increased environmental sustainability of the technology; conversely if *α* is elevated without green growth, it will result in more emissions production. Nevertheless, in the case of green growth, its impact should also be beneficial in reducing pollution levels.

To further strengthen our empirical model, we will proceed with the Romer endogenous growth model, where $g^P = \varphi^J H^J L$ & $r^{QU} = \varphi^{MQ} H^{MQ} L$ by employing these two conditions in Equ (13) and supposing s = 0; the following equation will be obtained:

$$r^U \leq 0 \, if \, H^{MQ} \geq \frac{\alpha}{\beta} \cdot \frac{\varphi^J}{\varphi^{MQ}} . H^J \quad (14)$$

Equ (17) indicates that sustainable development may be attained by allocating more resources or shares *(H)* to R&D initiatives promoting a sustainable environment and increasing revenues. The correlation between gross emissions and TI on net emissions is represented by *α*. The increasing values of *α* and *β* signify more efforts in advancing cleaner technologies. The following functional form is specified and is to be examined experimentally in this study based on our theoretical framework:

$$CO_{2ti} = \beta_1 GDP_{ti} + \beta_2 GDPH_{ti} + \beta_3 RE_{ti} + \beta_4 NRE_{ti} + \beta_5 TI_{ti} + \beta_6 HC_{ti} + \mu_{ti} \quad (15)$$

$$CO_{2ti} = \beta_1 GG_{ti} + \beta_2 GGH_{ti} + \beta_3 RE_{ti} + \beta_4 NRE_{ti} + \beta_5 TI_{ti} + \beta_6 HC_{ti} + \mu_{ti} \quad (16)$$

4. MATERIAL AND METHODS

4.1. Data Source and Variable Description

The present research examines the influence of RE, NRE, GG, TI, HC, and GDP on CO_2e in the GCC economies (Figure 2), utilizing a dataset from 1990 to 2022. These economies are chosen for this research due to their rich fossil fuel reserves and the extensive investigation of these resources for economic growth. Despite these countries having enormous fossil fuel reserves, recent research indicates that the GCC countries are investing significantly in TI and RE to mitigate pollution and transition to a greener economy. These economies are experiencing rapid economic growth, with their member nations witnessing rising income levels and elevated living standards. These characteristics significantly influence the attainment of the SDGs, hence validating the selection of these regions for this research. Furthermore, CO_2e is employed as an explained variable used to measure environmental deterioration, whereas RE, NRE, TI, GG, GDP, and HC are explanatory variables. The worldwide SDGs encompass all facets of socio-economic development in nations, and the interaction of multiple factors serves as effective indicators that substantially contribute to making GCC countries more sustainable. This research provides a comprehensive examination of the environmental factors in the GCC region and their impact on achieving the SDGs. An overview of the explained and explanatory variables is illustrated in Table 1.

4.1.1. Cross-sectional dependence (CSD) tests

The CSD denotes the existence of correlation across the entities or units within a dataset. It specifies circumstances in which observations are influenced by common characteristics or factors rather than being independent of one another (Ashraf et al., 2024).

Figure 2: Map of GCC regions

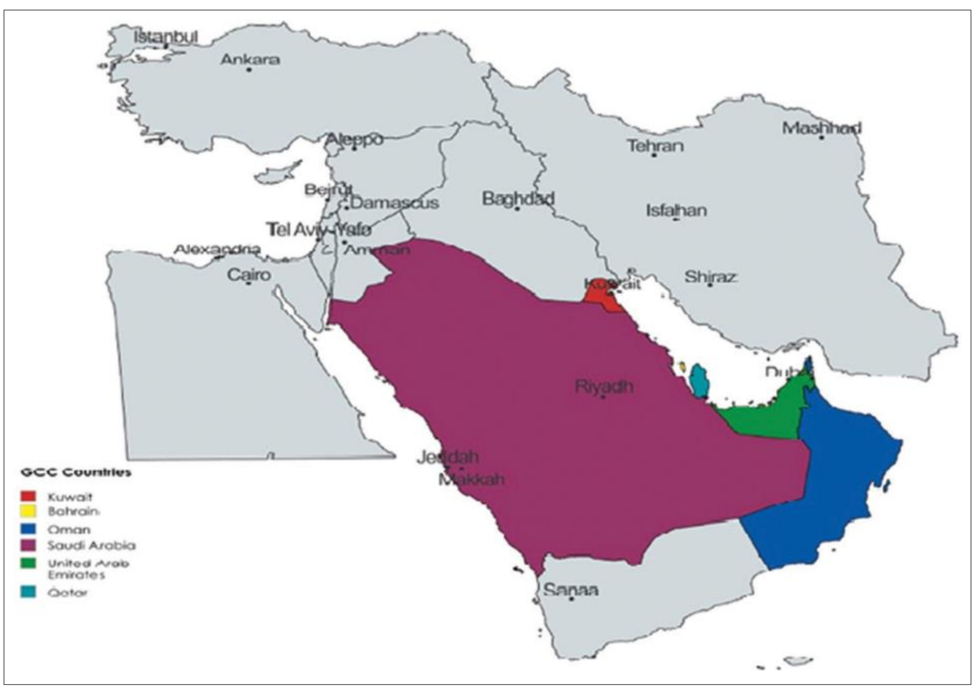


Table 1: Variables description

Variables	Acronyms	Measurement	Sources
Carbon dioxide emissions	CO_2e	Metric tons	World Development Indicators (WDI)
Renewable energy	RE	Proportion of aggregate energy	WDI
Nonrenewable energy	NRE	% age of cumulative energy, including natural gas, coal, and petroleum	WDI
Green growth	GG	Environmentally adjusted multifactor productivity growth (%)	OECD statistics (https://stats. oecd.org)[1]
Gross domestic product	GDP	Constant 2015$	WDI
Technological innovation	TI	Patents registered in environment-related technologies	OECD statistics
Human capital	HC	Human capital index, based on years of schooling and returns to education	PWT (2022)

CSD may arise in environmental or economic evaluations that concentrate on the performance of companies within a particular industry, influenced by overarching variables such as market dynamics, technology advancements, or legislative changes affecting all enterprises concurrently. Thus, as seen in Eqs. (17) and (18), Breusch and Pagan (1980) and Pesaran (2004) employed correlation coefficients to develop a specific CSD statistic to tackle the problem.

$$CSD = \sqrt{\frac{2M}{n(n-1)}}\left(\sum_{i=1}^{n-1}\sum_{k=i+1}^{n}\hat{\varepsilon}_{ik}\right) \quad n(0,1)i, k \tag{17}$$

$$R = \sqrt{\frac{2M}{n(n-1)}}\left(\sum_{i=1}^{n-1}\sum_{k=i+1}^{n}\hat{\delta}_{ik}\right)\left[\frac{(M-j)\hat{\delta}_{ik}^{2}-(M-j)\hat{\delta}_{ik}^{2}}{Var(M-j)\hat{\delta}_{ik}^{2}}\right] \tag{18}$$

The symbol $\hat{\varepsilon}_{ik}^{2}$ denotes the pairwise correlation of residuals derived from sample estimation by fundamental regression analysis.

4.1.2. Panel unit root tests

This research employs the cross-sectionally augmented Dickey-Fuller (CADF) and cross-sectionally augmented IPS (CIPS) methods to achieve this aim. These tests are beneficial as they acknowledge heterogeneity, address CSD, and minimize the probability of incorrect outcomes (Pesaran, 2004). Equation (19) below is the mathematical formulation of the CIPS approach:

$$\Delta Z_{i,t} = \Omega_{1} + \Omega_{1}EF_{i,t-1} + \Omega_{1}\overline{Z}_{t-1} + \sum_{j=0}^{p}\Omega_{i1}\Delta\overline{Z}_{t-j} + \sum_{j=1}^{p}\Omega_{i1}\Delta Z_{i,t-1} + \mu_{it} \tag{19}$$

$\overline{Z}$ demonstrates the average across the cross-sectional units.

Meanwhile, the basic model is presented in Eq. (20) as below:

$$Z_{i,t} = \Omega_{GTEC}GTEC_{i,t} + \Omega_{ECI}\overline{ECI}_{it} + \Omega_{HC}HC_{i,t} + \Omega_{REU}\overline{REU}_{it} \tag{20}$$

They can also be derived using the CIPS statistical test, as shown in Eq. (21) below:

$$\hat{C}IPS = \frac{1}{N}\sum_{i=1}^{N}CADF_{i} \tag{21}$$

Here, CADF denotes the test statistic. Equation (22) can be utilized to compute the CADF-based stationarity test as follows:

$$\Delta X_{i,t} = \eta_{i} + \hat{N}_{i}X_{i,t-1} + \delta_{i}\overline{X}_{t-1} + \sum_{j=0}^{s}\gamma_{i,j}\Delta\overline{X}_{t-j} + \sum_{j=1}^{s}\vartheta_{ij}\Delta X_{i,t-j} + \varepsilon_{i,t} \tag{22}$$

Where, $\Delta\overline{X}$ represents the average of the first-differenced values.

4.1.3. Westerlund cointegration approach

This study employs Westerlund's (2007) technique to evaluate the long-term relationship among RE, NRE, GG, TI, HC, GDP, and CO2e within an empirical framework. The Westerlund test incorporates four distinct statistics: two group statistics (Gt and Ga) and two panel statistics (P_t and P_a). The methodology outlined in Eqs. (23) and (24) accurately assess long-term relationships under the assumption of "no cointegration" and address CSD in panel data.

$$G_{\tau} = \frac{1}{N}\sum_{i=1}^{N}\frac{\hat{N}_{i}}{S.E.(\hat{N}_{i})} \text{ and } G_{a} = \frac{1}{N}\sum_{i=1}^{N}\frac{T\hat{N}_{i}}{\hat{N}_{i}(1)} \tag{23}$$

$$P_{\tau} = \frac{\hat{N}_{i}}{S.E.(\hat{N}_{i})} \text{ and } P_{a} = T\hat{N} \tag{24}$$

4.1.4. Cross-sectional autoregressive distributed lag (CSARDL) approach

The CSARDL approach is utilized to tackle slope heterogeneity and CSD effectively. Since the current research must account for CSD, the CSARDL technique is utilized because of its ability to manage these challenges through its associated effect estimators (Yao et al., 2019). The process begins with the specification of Eq. (25), as presented below:

$$W_{it} = \sum_{I=0}^{P_{W}}\delta_{I,i}W_{i,t-1} + \sum_{I=0}^{P_{U}}\Omega_{I,i}U_{i,t-1} + \varepsilon_{i,t} \tag{25}$$

Furthermore, to clarify the ARDL method, Eq. (25) is reformulated using the cross-sectional means of all explanatory

1 https://www.oecd.org/en/data/indicators/patents-on-environment-technologies.html

Table 2: Descriptive statistics

Statistics	CO_2e	RE	NRE	GG	GDP	TI	HC
Mean	4.215	58.325	20.658	2.547	3.448	3.265	9.526
Median	4.236	56.145	13.021	2.369	3.652	1.025	9.874
Maximum	7.878	78.325	36.214	15.014	2.254	13.985	12.023
Minimum	2.547	45.502	23.654	3.025	1.269	7.547	5.658
Standard deviation	2.036	0.214	8.214	1.214	2.652	4.120	1.256
Skewness	0.145	1.654	0.218	0.236	0.321	1.552	1.332
Kurtosis	1.256	8.214	2.365	1.220	1.332	3.523	2.010
Jarque-Bera	12.658	13.569	11.014	12.023	9.326	36.558	13.558

variables, as shown below. This technique addresses the potential for inaccurate, biased, and inconsistent parameter estimations resulting from CSD within the panel (Chudik and Pesaran, 2015). Nevertheless, the CSD issue persists if this technique is executed utilizing Eq. (26):

$$W_{it} = \sum_{l=0}^{P_W} \delta_{l,i} W_{i,t-1} + \sum_{l=0}^{P_U} \Omega_{l,i} U_{i,t-1} + \sum_{l=0}^{P_V} \Psi_i^{A} \overline{IV}_{i,t-1} + \varepsilon_{i,t} \quad (26)$$

Equation (13) illustrates both the independent and dependent panel variables, with P_W, P_U, and P_V denoting the lagged terms of each component, and $\overline{IV}_{i,t-1} = (W_{i,t-1}, U_{i,t-1})$. In this context, $W_{i,t}$ represents the dependent variable, CO_2e, whereas $U_{i,t}$ includes variables such as RE, NRE, TI, GG, GDP, and HC. The term $\overline{V}$ captures the average CSD, accounting for spillover effects within the dataset. The long-run parameters are subsequently derived from the short-run coefficients. Consequently, the average is presented in Eq. (27) below:

$$\Pi_{CS-ARDL,i} = \frac{\sum_{l=0}^{P_U} \Omega_{l,i}^{P_w}}{1 = \sum_{l=0}} \delta_{l,i} \quad (27)$$

In addition, the group average is expressed in Eq. (28) as shown below:

$$\Pi_{MG} = \frac{1}{N} \sum_{l=0}^{N} \Pi_i \quad (28)$$

The short-run parameters are presented in Eqs. (28-32) as follows:

$$W_{it} = \theta_{it} \left[W_{it-1} - \Omega_i U_{i,t-1} \right] - \sum_{l=1}^{PW-1} \delta_{l,i} \Delta W_{i,t-1} + \sum_{l=0}^{PU} \Omega_{l,i} \Delta_I U_{i,t}$$

$$+ \sum_{I=0}^{P_V} \Psi_i^{A} \overline{IV}_{i,t-1} + c_{i,t} \quad (29)$$

Δ_I = t-(t-1)

$$\lambda_i = -\left(1 - \sum_{l=1}^{p_w} W_{l,i}\right) \quad (30)$$

$$\Pi_i = \frac{\sum_{l=0}^{P_U} \Omega_{l,i}}{\lambda_i} \quad (31)$$

$$\vec{\Pi} MG = \frac{1}{N} \sum_{i=0}^{N} \Pi_i \quad (32)$$

Table 3: VIF outcomes

Regressors	VIF	1/VIF
RE	2.935	0.254
NRE	2.547	0.325
GG	2.387	0.745
GDP	2.541	0.655
TI	1.325	0.987
HC	2.145	0.547
Mean VIF	2.313	

Likewise, the CSARDL framework maintains the pooled mean group, and the equation incorporates the error correction mechanism [ECM (−1)] to represent the long-term equilibrium adjustment.

5. RESULTS AND DISCUSSIONS

5.1. Descriptive Statistics Outcomes

The descriptive statistics for all regressors and regressand: RE, NRE, TI, GG, HC, GDP, and CO_2e are shown in Table 2. The mean, median, standard deviation, maximum, minimum, total sum, sum of squared deviations, probability, skewness, kurtosis, count of observations, and Jarque-Bera statistic are all included. The average of the variables ranges from 2.547 (GG) to 58.325 (RE), while the SD ranges between 0.214 (RE) and 8.214 (NRE). The distributions appear to be approximately symmetrical, as indicated by the skewness values, which are predominantly close to 0. In contrast, Kurtosis values exceeding 3 suggest distributions with heavier tails, unlike a normal distribution. The JB test reveals that all variables exhibit deviations from normality, indicating a minimal likelihood of conforming to a normal distribution. The sum indicates the dataset's total, while the sum of squared deviations represents its variability.

5.2. Multicollinearity Analysis

Table 3 displays the outcomes of the variance inflation factor (VIF) study, which evaluates potential multicollinearity among the variables. Furthermore, a robust correlation among independent variables results in multicollinearity. The VIF values demonstrate the extent of this correlation for the chosen variables; higher VIF values signify more robust bivariate relationships among the variables. The findings specify that the RE possesses the highest VIF value (2.935), followed by NRE (2.547), HC (2.145), GDP (2.541), GG (2.387), and TI (1.325). The average VIF of 2.313 for all variables indicates an acceptable multicollinearity level. Although multicollinearity is a consideration, the VIF values in this study do not indicate a critical issue that would substantially undermine the reliability of the results. Still, this study exercises caution when interpreting elasticity estimates and considers potential collinearity effects in concluding.

5.3. CSD Analysis

The Pesaran Scaled LM, Pesaran CSD, Breusch-Pagan LM, and Bias-Corrected Scaled LM tests were performed to evaluate CSD among the chosen series. The results in Table 4 show that each experiment provides solid evidence that no CSD exists for any of the selected variables. The findings corroborate the regional linkages and spillover effects of the GCC regions.

5.4. Unit Root Analysis

Table 5 displays the outcomes of the panel CADF and CIPS stationarity tests. The findings suggest that all selected indicators are stationary at 1st difference. This indicates that the next step is to move towards a long-run cointegration technique to investigate whether all potential panel variables have maintained their long-term relationships.

5.5. Westerlund Cointegration Outcomes

The Westerlund (2007) technique yields reliable and consistent results, despite its heterogeneity and cross-sectional nature, making it suitable for assessing cointegration when all explanatory and explained variables are constant at their initial level of integration. Table 6 demonstrates the rejection of the null hypothesis of no long-run cointegration for the *Gτ, Ga, and Pτ* statistics, whereas for *Gτ and Pτ* under both continuous and trend specifications. This indicates a sustained relationship between the selected variables. Thus, a persistent correlation appears among RE, NRE, TI, GG, HC, GDP, and CO_2e for GCC regions.

Table 4: CSD outcomes

Variables	Breusch-Pagan LM		Pesaran Scaled LM		Pesaran CSD	
	Stat	Prob	Stat	Prob	Stat	Prob
CO_2e	23.225***	0.000	65.147***	0.000	3.654***	0.000
RE	12.254***	0.000	85.412***	0.000	8.221***	0.000
NRE	20.558***	0.000	58.658***	0.000	5.145***	0.000
GG	13.654***	0.000	70.441***	0.000	16.587***	0.000
GDP	11.203***	0.000	15.426***	0.000	5.213***	0.000
TI	45.269***	0.000	95.332***	0.000	9.254***	0.000
HC	30.547***	0.000	87.002***	0.000	10.366***	0.000

***P<0.01

5.6. CSARDL Outcomes

This research utilizes the CSARDL methodology to assess the long-term coefficients or elasticities (Table 7). In the long term, RE, NRE, TI, GG, HC, and GDP influence CO_2e in the GCC economies.

The coefficient values show that a 1% increase in RE tends to mitigate CO_2e by 1.256%. On the other hand, the coefficient value of NRE indicates that a 1% increase in NRE results in a 2.658% surge in CO_2e. It may be argued that reducing pollution results from RE's role in lowering energy intensity, hence promoting ecological sustainability. These results are consistent with (Anwar et al., 2021; Dong et al., 2022; Bekun and Alola, 2022; Liu et al., 2020; M´orawska, 2020; and Yang et al., 2018). In the GCC regions, growing concerns regarding the environmental impacts of CO_2e necessitate adopting clean energy as a key alternative to unsustainable energy sources. An increased share of RE in the energy portfolio is an effective strategy to maintain the objective of restricting global warming to below 2◦C, thereby ensuring a pristine environment for future generations. Transformation from unsustainable energy sources to sustainable ones can help mitigate the pace of global warming and reduce environmental deterioration. Given that the price of energy derived from green sources is presently inferior to that of unsustainable ones, and that the cost of crude oil per barrel approximates $3631, a viable strategy to achieve the objectives is to extend financial assistance to research institutions, organizations, and policy-makers to facilitate the generation of RE at reduced cost. Furthermore, RE sources eliminate the need for extensive drilling or mining, preventing harm to ecosystems, species, and natural landscapes. Utilizing RE enables the conservation of these natural ecosystems. Additionally, RE refers to promoting sustainable energy sources and avoiding the depletion of unsustainable resources, such as fossil fuels (Zhu et al., 2024).

Table 5: Unit root tests outcomes

Indicators	Constant				Constant and trend			
	Level		1st Diff		Level		1st Diff	
	CIPS	CADF	CIPS	CADF	CIPS	CADF	CIPS	CADF
CO_2e	−2.325	−2.201	−3.225***	−5.455***	−3.125	−2.589	−3.654***	−4.852***
	(0.857)	(.215)	(0.000)	(0.000)	(0.266)	(0.218)	(0.002)	(0.000)
RE	−1.547*	−2.547	3.145***	−4.325***	−3.332	−1.541	−3.552***	−3.652***
	(0.086)	(0.158)	(0.000)	(0.002)	(0.136)	(0.198)	(0.000)	(0.000)
NRE	−3.547	−2.985	−2.65***	−5.985***	−2.012*	−2.663	−2.965***	−4.623***
	(0.852)	0.877)	(0.006)	(0.007)	(0.084)	(0.322)	(0.000)	(0.000)
GG	−3.225	−1.541***	−3.985***	−5.102***	−1.658	−2.956**	−3.214***	−5.213***
	(0.930)	(0.006)	(0.000)	(0.000)	(0.855)	(0.025)	(0.000)	(0.007)
EG	−4.213	−2.012	−1.365***	−2.547***	−3.458**	−2.369	−5.210***	−2.364***
	(0.140)	(0.224)	(0.000)	(0.000)	(0.036)	(0.217)	(0.001)	(0.000)
TI	−3.654	−3.221	−3.631***	−7.652***	−3.652	−3.214	−4.693***	−4.962***
	(0.151)	(0.255)	(0.000)	(0.000)	(0.995)	(0.366)	(0.000)	(0.000)
HC	−2.014	−2.002	−4.125***	−4.125***	−4.214	−2.589	−3.201***	−5.213***
	(0.975)	(0.856)	(0.000)	(0.000)	(0.256)	(0.889)	(0.000)	(0.000)

***P<0.01, **P<0.05, *P<0.10

Table 6: Westerlund cointegration outcomes

Stats	Values	z-values	P-values	Robust P-values
Without constant				
Gt	−3.256***	−1.236	0.127	0.000
Ga	−2.654*	−0.213	0.136	0.086
Pt	−4.123***	1.177	0.445	0.005
Pa	−3.589***	−0.325	0.874	0.008
With constant				
Gt	−3.589	0.07	0.985	0.15
Ga	−2.659***	−1.658	0.456	0.000
Pt	−1.023**	1.023	0.887	0.026
Pa	−3.547***	1.113	0.998	0.002

***P<0.01, **P<0.05, *P<0.10

Table 7: CSARDL outcomes

Variables	Coeff.	t-stat.	P-values
Long-run outcomes			
Regressand: CO_2e			
RE	−1.256***	2.005	0.000
NRE	2.658***	2.119	0.002
GG	−6.325***	1.569	0.000
GDP	3.125***	2.541	0.006
TI	−5.214***	3.025	0.000
HC	−3.256***	3.569	0.006
Short-run outcomes			
RE	−1.825***	3.658	0.000
NRE	2.654***	2.156	0.000
GG	−1.236***	3.652	0.000
GDP	2.032***	1.254	0.001
TI	−1.547***	1.256	0.007
HC	−3.658***	2.301	0.000
ECT (−1)	−0.255******	−3.002	0.000

Robust Standard Errors used. ***P<0.01

The coefficient of the TI demonstrates an inverse correlation with CO_2e for GCC regions, indicating that a 1% increase in TI leads to a 5.214% reduction in CO_2e. This suggests that the environmental impact will decrease as the GCC adopts more sustainable technologies. This outcome may significantly impact governments and policymakers within the GCC economies. It implies that encouragement and adoption of novel technologies may serve as a significant way to diminish CO_2e and promote sustainability. The outcomes are consistent with (Cheng et al., 2022; Dong et al., 2022). While TI has been vital to GCC's modernization and economic growth, it has also played a significant role in these economies' rising CO_2e. Industries that rely heavily on fossil fuels have seen their energy consumption rise in tandem with the rapid industrialization brought about by TI. Moreover, the GCC continues to rely on carbon-intensive energy sources because its rapid industrialization has outpaced the adoption of RE sources, even though green technology has made significant strides. Therefore, technological advancement has increased CO_2e and caused environmental damage in the GCC despite the benefits.

The outcomes of GG indicate a detrimental effect on CO_2e, as a one-unit increase in GG leads to a decrease in CO_2e by 6.325 units. GG is considered an essential strategy for achieving sustainable development because of its capacity to foster economic growth and environmental sustainability. Moreover, GG has the potential to provide significant social and financial advantages, since it is seen as economically efficient and vital for the future of the GCC countries. The outcomes of this study are consistent with (Jouvet and De Perthuis, 2013; Kang and Lee, 2021). The GCCs' attempts to decrease CO_2e are admirable, yet the GCC economies significantly contribute to GHGe. In this context, the findings of this study may guide the GCC countries in formulating effective measures to regulate CO_2e.

The coefficient of HC shows an inverse relation with CO_2e, as a 1% rise in HC leads to a 3.256% reduction in CO_2e. Higher education and expertise can foster heightened ecological awareness, a profound understanding of the HC on climate, and the expansion of creative and novel approaches to environmental issues. The existing researchers, for instance, Sarkodie et al. (2020), Abdouli and Omri (2020), Sarwar et al. (2020), Nathaniel et al. (2021), and Saqib and Usman (2023) concluded similar findings. Furthermore, people with extensive knowledge and expertise will most likely participate in environmentally advantageous areas such as green energy and sustainable agriculture. Additionally, human resources can promote the advancement of novel technologies that reduce environmental pollution. HC can be employed to conceptualize and manage fuel-saving infrastructure and transport networks, as well as develop and implement cutting-edge RE technology. Moreover, HC executes sustainable strategies across the transportation and agriculture sectors. An individual proficient in sustainable agriculture can minimize pesticide and fertilizer usage, whereas someone knowledgeable in green manufacturing may devise and execute eco-friendly production methods. Integrating the RE and HC can promote a more environmentally responsible and sustainable economy. To strengthen HC and promote the advancement of a better and more sustainable future, the GCC economies must prioritize investing in education and skills development.

Lastly, the results indicate that GDP positively influences CO_2e, as a one-unit increase in GDP causes a 3.125-unit increase in CO_2e. These outcomes coincide with (Amin et al., 2025; Sharma et al., 2022; Yu et al., 2023). The positive impact of GDP growth on the increasing CO_2e is justifiable, since the GCC economies are recognized as the most rapidly expanding, with their economic development having markedly intensified over the last four decades. Their real per capita income increase has stimulated resource usage across all economic sectors. Consequently, these GCCs have become the principal energy consumers and the regions with the increasing CO_2e. The estimated results indicate that the sluggish per capita income growth and inadequate environmental standards in these countries diminish the correlation between ecological deprivation and GDP.

5.7. Robustness Analysis

For robustness analysis, we employed Common Correlated Effect Mean Group (CCEMG) and Augmented Mean Group (AMG) estimation techniques are presented in Table 8. The findings of AMG explain that the coefficient values of RE, NRE, GG, GDP, TI, and HC are 0.470, 0.189, 0.223, 0.355.,044, and 0.0220, which further elaborate that a one-unit increase in these variables mitigates CO_2e with respective statistics. On the other hand, the CCEMG outcomes show that a 1% increase in RE, GG, TI, and HC results in decreases of 0.0250%, 0.654%, 0.136%, and

0.254%, respectively, in CO_2e. Whereas, a 1% increase in NRE and GDP results in a 0.336% and 0.354% decrease in CO_2e, respectively. Furthermore, the value of Wald test indicates the model's significance. The outcomes are consistent with Kang and Lee (2021), and Sharma et al. (2022). A brief summary of empirical findings is illustrated in Figure 3.

6. CONCLUSION, POLICY IMPLICATIONS, AND LIMITATIONS

This study contributes to the current literature on sustainable development by examining the association amongst RE, NRE, GG, TI, HC, GDP, and CO_2e for the GCC economies from 1990 to 2022. The lead-lag correlations between the mentioned indicators can be investigated using the analytical approach known as CSARDL. The findings indicate a strong negative relationship amongst RE, TI, GG, HC, and CO_2e. Whereas, a direct relationship is found between NRE, GDP, and CO_2e, suggesting a substantial increase in the pollution levels in the GCC regions.

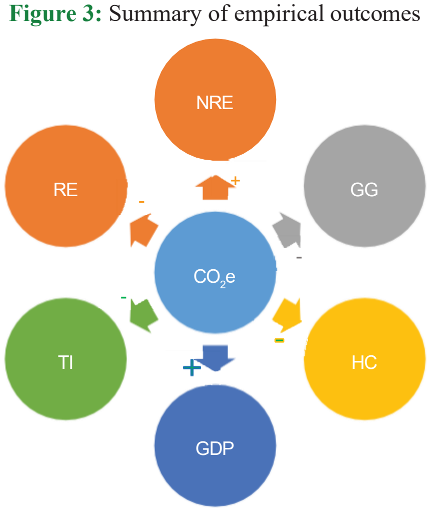
The estimated results have significant policy recommendations. The GCC economies comprise emerging economies that must integrate further technological advancements into their current energy sectors to improve energy efficiency and invest in green energy sources to produce greater amounts of renewable energy. Furthermore, one of the most efficacious strategies for mitigating environmental degradation is to impose a carbon tax, which motivates industries to diminish their emissions by increasing the cost of pollution. Additionally, countries may incentivize the use of advanced technologies by requiring a specific proportion of RE in their energy mix. Moreover, energy storage, electric cars, carbon sequestration, and other environmentally friendly technologies may receive financing from governments for their R&D. Governments may incentivize the purchase of environmentally friendly technology, such electric cars or energy-efficient appliances, by offering subsidies or tax incentives, which can lower the prices of these products and make them more accessible. Furthermore, governments can leverage their purchasing power to encourage the utilization of novel technologies by mandating that traders adhere to specific ecological criteria. Additionally, states may establish and enforce policies to mitigate the ecological impacts of certain businesses, like imposing emissions restrictions on power plants or setting fuel economy standards for automobiles. The development of cleaner technologies within the transportation framework, including waste management, recycling, electric vehicles, and wave energy production, should be encouraged. The administrators of these nations may also increase their subsidies for R&D across both commercial and institutional entities, thereby promoting sustainable development across the regions.

Table 8: Robustness analysis outcomes

Variables	AMG			CCEMG		
	Coeff.	t-stat.	P-values	Coeff.	t-stat.	P-values
RE	−0.470***	3.201	0.000	0.025***	−6.541	0.000
NRE	0.189***	2.654	0.006	0.336***	4.523	0.000
GG	−0.223**	3.354	0.025	0.654***	−2.569	0.000
GDP	0.355*	2.547	0.084	0.354***	1.541	0.000
TI	−0.044***	4.569	0.000	0.136***	−3.215	0.000
HC	−0.022***	3.47	0.000	0.254***	−2.547	0.000
Wald test	------	31.256	0.000		13.025	0.000

***P<0.01, **P<0.05, *P<0.10

Figure 3: Summary of empirical outcomes



Additionally, green growth reduces CO_2e in GCC countries. One of the most effective ways to achieve the SDGs is through GG, which has the potential to boost the economy while also protecting the environment. Moreover, green growth is crucial for the economic future of the GCC regions and is considered an economically efficient approach; it may also yield significant social and economic benefits for these economies. Policy-makers and governments must encourage industries that prioritize sustainable production. Additionally, plan and direct the development of policies that facilitate environmentally friendly manufacturing and investment in feasible initiatives. It is crucial to evaluate policy strategies that amplify the positive impact of green growth on emissions mitigation, particularly when there is only a weak correlation between the two. By promoting green growth and implementing these initiatives, GCC economies can accelerate sustainable development while safeguarding air quality.

Regarding the energy transition, governments may establish ambitious objectives and directives for implementing cleaner energy sources. Such objectives may be to a proportion of overall energy consumption or a specific quantity to be achieved within a particular constraint. This method provides a robust signal to shareholders and reinforces the development of greener energy infrastructure. Furthermore, implementing feed-in tariffs may give a stable payment rate for RE producers, thereby promoting clean energy schemes. This approach mitigates financial risks associated with green energy initiatives. Furthermore, the GCC economies may impose tax incentives and subsidies to promote the use of advanced technologies. This may comprise tax credits for the purchase of green energy equipment, reduced taxes on renewable energy output, or direct subsidies to support the establishment and growth of RE systems. Furthermore, promoting the development of energy-efficient technology helps mitigate the intermittent production issues associated with renewable energy sources. Governments should launch educational initiatives to raise public and community understanding of the environmental implications of non-renewable energy sources and the benefits of cleaner energy to encourage their adoption. If appropriately implemented, these initiatives have the potential to reduce pollution associated with traditional energy sources, promote clean energy utilization, and lessen reliance on NRE energy.

Moreover, the advancement of human capital can be achieved through several strategies that simultaneously improve the atmospheric quality. These strategies comprise investing in training programs, financing research and development, and providing entrepreneurial assistance. Moreover, enacting ecological regulations, advancing employment initiatives, establishing fuel-saving schemes, and executing sustainable agricultural strategies can collectively contribute to achieving SDGs in GCC economies. By implementing these measures, states may foster a sustainable future in which development and ecological conservation coexist. Offering educational and training options to employees may enhance human capital. Promoting investment in sustainable enterprises and initiatives safeguards the environment. This may include offering incentives for investment in environmentally friendly technology and sustainable enterprises. Moreover, enforcing ecological restrictions help to save ecosystem, which may include restrictions on increasing pollution, leftover disposal, and further ecological effects.

This research has a few limitations. Firstly, this study considers CO_2e as an indicator of climate change; however, other climate change indicators, such as the ecological footprint, ecological intensity, or ecological efficiency, are also considered to obtain policy-oriented or more robust findings. Secondly, this study examines the influence of the drivers of CO_2e varies according to the econometric methodology used. Future research may investigate the determinants of CO_2e by utilizing various econometric techniques, including the wavelet coherence, Fourier transforms, and nonlinear analysis.

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