



The asymmetric effect of ICT on CO₂ emissions in the context of an EKC framework in GCC countries: the role of energy consumption, energy intensity, trade, and financial development

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Received: 29 November 2022 / Accepted: 8 May 2023 / Published online: 1 June 2023

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Abstract

This study examines how “information and communication technology (ICT)” affects carbon dioxide (CO₂) emissions in Gulf Cooperation Council (GCC) nations asymmetrically, controlling energy consumption, its intensity, trade, and financial development following an environmental Kuznets curve (EKC) approach. It employs panel data covering 1995–2019, 2nd generation unit root, Westerlund cointegration tests, nonlinear pooled mean group (PMG) estimate, and Dumitrescu-Hurlin causality check. The Westerlund test validates a long-run association among variables. The study confirms the EKC proposition for the GCC countries. It reveals that a decrease in CO₂ emissions is associated with both positive and negative parts of ICT and the expansion of financial development. While per capita GDP increases pollution, squared GDP per capita reduces it; energy consumption, intensity, and trade amplify carbon emissions. D-H causality check yields several bidirectional and one-way causalities and verifies the robustness of PMG outcomes. Our findings suggest that promoting ICT becomes one of the critical techniques to decrease CO₂ emissions in GCC nations due to its significant negative influence on CO₂ emissions.

Keywords ICT · CO₂ emissions · Asymmetric impact · EKC hypothesis · GCC countries

Introduction

Information and communication technology (ICT) has progressed significantly during the past three decades. Globalization has led to an increased reliance on ICT by developed and developing economies to boost productivity and energy efficiency across various economic sectors. According to empirical research, using ICT can help drive economic development. Thanks to ICT, we can predict a reduced planetary distance, connecting people and societies closer (Nasir & Kalirajan, 2016). Practically various sectors of a

modern economy are dependent on the use of ICT, including but not limited to trade, external investment, and financial progress. The expansion of access to information, the facilitation of natural resource uses, and the promotion of economic growth are all results of the proliferation of ICT (Latif et al., 2018). The advancement of ICT has resulted in structural changes in the industrial sector, strengthening the economy (Jorgenson & Vu, 2016; Zhang & Danish, 2019) and contributing to the advancement of humankind (Iqbal et al., 2019).

Although improvements in ICT support economic progress, the environmental effects of these technologies are significant around the globe (Lee & Brahmastrane, 2014). ICT has a remarkable impact on the environment and spectacular implications for income growth and human advancement. It might positively or negatively impact the environment or even be neutral. For instance, Godil et al. (2020), Chien et al. (2021), and Shehzad et al. (2022) showed that using ICT to minimize pollution emissions was environmentally favorable. As a result, many nations are considering adopting ICT to reduce their carbon footprint and safeguard the environment.

Responsible Editor: Eyup Dogan

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In contrast, there are also situations where ICT causes environmental quality to decline. For example, Park et al. (2018), Asongu et al. (2018), Arshad (2020), and Alatas (2021) argued that ICT continued to be harmful to environmental quality since it increased airborne carbon emissions. Moreover, Amri et al. (2019) noted that ICT was environmentally friendly because its influence on CO₂ emissions was minimal. As a result, there is still room for further research into how ICT affects environmental quality.

ICT impacts CO₂ emissions primarily in two ways: through the utilization effect and the replacement effect. Both may affect the atmosphere in positive and negative ways. Initially, the production of ICT devices and machinery results in environmental pollution while using it. Next, energy consumption and the disposal of e-waste during replacement cause environmental pollution (Anon Higon et al., 2017). The manufacturing and use of ICT are thought to be responsible for 2% to 3% of all environmental pollution on the planet, while the quantity of energy required to run ICT devices has increased by 7% annually (Ozcan & Apergis, 2018). Two environmental hazards that are likely to increase in the future are mobile data traffic and enormous data centers (Lennerfors et al., 2015).

ICT use has a substitution effect that causes automation (Salahuddin & Alam, 2015), mobilization, and decarbonization (Ozcan & Apergis, 2018; Zhang & Liu, 2015). Innovative transportation technology includes traffic cameras, global positioning systems, and travel agencies, whereas online purchasing, e-commerce, teleconferencing, and e-business reduce outdoor activities. Also, the increased energy efficiency driven by using and improving ICTs helps reduce CO₂ emissions (Danish et al., 2018b; Zhang & Liu, 2015). ICT's effects on CO₂ emissions have recently drawn more consideration from academics and researchers. There are few studies on the role of ICT in decreasing CO₂ emissions in the Arabian Gulf region, even though ICT's economic and environmental effects have been thoroughly investigated across many countries. Thus, the study is aimed at examining the impact of ICT on CO₂ emissions in GCC economies.

The focus of studies on environmental sustainability has broadened from a single nation to the whole world (Sarkodie, 2018). The Gulf states possess one-third of the world's known crude oil reserves and twenty percent of the global gas reserves, which make them major global energy exporters. Recent data suggests that by 2020, the GCC nations had exported almost 13 million barrels of oil daily, 18% of total global output (BP, 2022). As a result, these countries have a high per capita income, which enables them to have a penchant for high-tech and luxury goods. Thanks to the countries' prodigious oil exports, these countries have integrated with the global markets and adopted ICT uses. Consequently, the GCC region is one of the world's most

advanced areas in adopting and using ICT (Ebaidalla & Abusin, 2022).

Much research has established the connection between energy use and pollutant discharges (Ali et al., 2022; Islam, 2021). Due to economic growth, there have been significant upsurges in energy consumption during the past three decades (Islam and Ali, 2011; Islam and Islam, 2022), which are thought to be the primary drivers of the rising environmental degradation that endangers both people and the ecology. The GCC countries are the leading producers and worldwide exporters of non-renewable energies from natural gas, petroleum, and other liquids. During 1995–2021, the annual average energy production amounted to 48.38 quadrillions Btu, of which 99.98% was sourced from natural gas, petroleum, and other liquids, while energy consumption accounted for only 30.22% of the production, and the lion's share of the energy production was exported globally. Many academics have looked into the influence of energy use on environmental excellence; non-renewable energy, in particular, has been a significant source of environmental degradation worldwide. They have shown that energy use contributes positively to environmental degradation such as Jalil and Feridun (2011), Shahbaz et al. (2014), Manuel et al. (2016), Javid and Sharif (2016), Armeanu et al. (2018), Rahman et al. (2019), Jaruwan (2020), Salari et al. (2021), Islam (2021), Jiang, et al. (2022) and Adeleye et al. (2023). Consequently, it seems to be a vital exercise to investigate its impact on air pollution in GCC countries.

The extent of energy used for one unit of production and energy intensity are employed to assess how inefficiently an economy consumes its energy, while using energy, high energy intensity indicates high GDP costs and vice versa. Yet, high energy intensity—which is the cause of high pollutant emissions in the environment—leads to increased manufacturing output in the form of GDP, whereas low-energy-intensity nations have labor-intensive industries. A product's energy intensity is established by the energy required to generate it; therefore, using less energy to create it reduces the intensity. It has been extensively studied how energy intensity affects economic growth, but less is known about how it affects the environment. Environmental effects of energy intensity have gotten less interest even though there is a substantial amount of study on the influence of energy use on the environment. This may be because energy use and intensity are viewed from the same perspective. The effect of energy intensity on the environment was explored in a few recent studies, such as Dogan and Shah (2021), who revealed that energy intensity negatively impacted the ecological footprint, and Shokoohi et al. (2022) and Danish et al. (2022), who found that it had a considerable and adverse effect on the environment. So, this study intends to examine the potential environmental impacts of energy intensity on the GCC countries.

The literature covers the numerous ways that CO₂ emissions are impacted by financial development (FD). Easy credit is a byproduct of financial expansion and hastens to purchase automobiles and home equipment. These goods and products lead to a convenient lifestyle and consume additional energies, which increases the amount of CO₂ released into the atmosphere. Moreover, in a time of financial expansion, access to cheap financing creates opportunities for expanding firms, which use a lot of energy and emit more CO₂. Thus, financial development causes environmental pollution (Zhang, 2011; Javid and Sharif, 2016; Khan et al., 2018; Islam, 2022a; Islam, 2022b). However, the acceleration of investments in R&D and green technologies may also result from financial growth, further enhancing the positive impression on environmental quality (Tamazian et al., 2009; Jalil and Feridun, 2011; Shahbaz et al., 2013; Li et al., 2015; Abbasi & Riaz, 2016). Thus, the impact of FD on CO₂ is also inconclusive; hence, this study scrutinizes its effects on CO₂ emissions in GCC countries.

Trade liberalization and openness typically influence economic growth by causing the manufacturing sector (Islam, 2022c), which produces a large amount of air pollution, to grow. The GDP rises along with trade openness, which raises greenhouse gas emissions from the manufacturing sector. As a result, trade openness is frequently employed in research as a factor influencing environmental contamination, and the literature extensively examines its effects. Most of the work already in existence has shown how it affects pollution and stated that trade openness has a favorable impact on it. Shahbaz et al. (2014), Zhang (2018), Tachie et al. (2020), and Appiah et al. (2022) are a few examples of these works. The other literary pieces conclude that it lowers the pollution level. For instance, Yu et al. (2019) had a favorable direct impact on CO₂ emissions but a negative indirect effect through income on the latter. Due to the more significant indirect effect in the Commonwealth of Independent States, the total impact on pollution remained negative. However, a third group of investigations revealed no difference in the pollution level, either positive or negative. For example, Javid and Sharif (2016) found no evidence that trade openness impacted CO₂ emissions in Pakistan, and Zhang (2021) found no evidence in China. Hence, it is also unclear how trade openness affects environmental pollution. This study pursues to shed some light on the subject in the context of the GCC countries.

This study is aimed at investigating ICT's effects on CO₂ emissions in GCC economies in an "environmental Kuznets curve (EKC)" framework. In the effort of Kuznets (1955), the correlation between economic growth and income disparity showed a reversed U-shaped pattern, refined by Grossman and Krueger (1991) to describe the link between income level and environmental quality termed the EKC hypothesis. Many researchers across the world carried out

the examination of the EKC proposition from diverging perspectives that revealed contrasting outcomes. For example, Jalil and Feridun (2011), Shahbaz et al. (2014), Javid and Sharif (2016), Zhang (2018), Armeanu et al. (2018), and Dogan and Inglesi-Lotz (2020) maintained the EKC proposition, while Al-Mulali et al. (2015), Zoundi (2017), Ozokcu and Ozdemir (2017), and Aruga (2019) reported no evidence supportive of the EKC theory. The EKC proposition allows for more than just several explanatory factors. Accordingly, this study uses four additional independent variables: ICT, energy use, trade openness, and financial development. The novelty of this study is (1) it considers the asymmetric behavior of ICT, (2) instead of using several components of ICT, it formulates and uses a composite ICT index based on principal component analysis (PCA), and (3) it employs an EKC framework for the first time to examine ICT-CO₂ nexus for the GCC countries.

To realize the research, the study utilizes the 2nd-generation unit root and Westerlund cointegration tests, nonlinear pooled mean group (PMG) estimate, and Dumitrescu-Hurlin causality check. The remainder of the study is prepared as follows: "The state of ICT and CO₂ emissions in GCC nations" describes the state of ICT and CO₂ emissions in GCC nations, "Review of recent literature" reviews the recent literature, "Data and methods" discusses the data and methods used in the study, "Results and discussions" presents the asymmetric findings and comments for both the long and short-runs, and "Conclusion" wraps up the study with policy recommendations.

The state of ICT and CO₂ emissions in GCC nations

ICT refers to the infrastructure and the processes that make modern computing smooth and easy. It has several subtypes; each contributes to the ease with which information may be communicated. Some examples are the telephone, internet, radio, television, etc. Usually, fixed telephone subscriptions (FTS) (per 100 people), cellular phone subscriptions (CPS) (per 100 people), internet users as a percentage of the population (IU), and medium- and high-tech exports as a fraction of total manufactured exports (MHTE) are used as a proxy for ICT in the literature. The trends of these four variables across the GCC nations are exhibited in Fig. 1. It reveals that there happens a significant increase in the development of ICT during the last three decades. However, for econometric analysis, we combine these four proxy variables into a composite ICT index using PCA reported in "Data and methods."

Figure 2 provides the pattern of CO₂ emissions, reported in metric tons per person, demonstrating a mixed behavior during the study period, with a relatively stable pattern across the GCC nations. However, we have specified the variable in more detail in Table 1 with its descriptive statistics.

Fig. 1 Trends of ICT components in GCC nations during 1995–2019

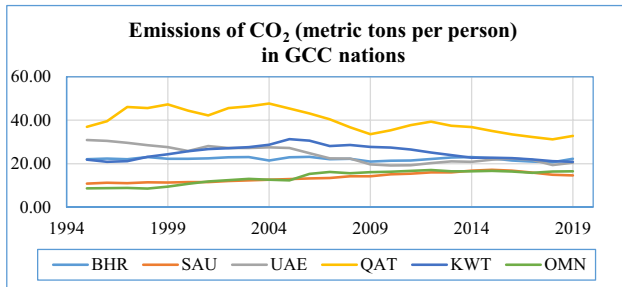
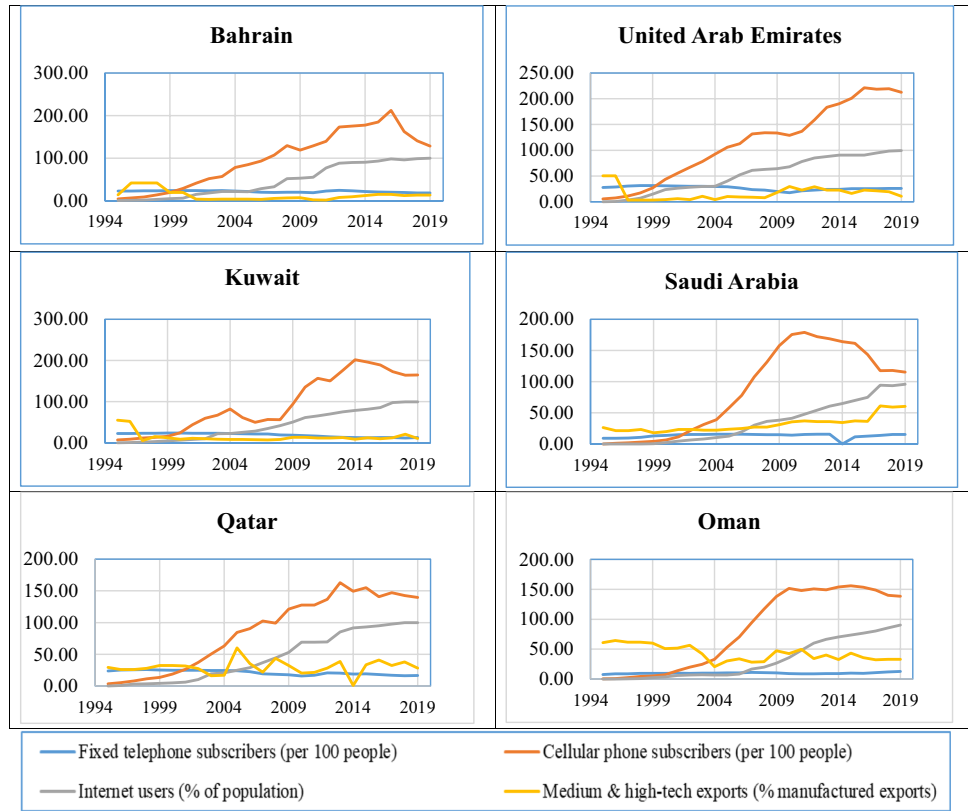


Fig. 2 Emissions of CO₂ (metric tons per person) in GCC nations

Review of recent literature

Much research has been carried out to look at the outcome of ICT on the environment. We look at the relevant pieces of related research to establish the precise influence that ICT has had on environmental pollution.

Al-Mulali et al. (2015) demonstrated that the retail sale of ICT produced a sizeable negative impression on CO₂ emissions in industrialized countries but no meaningful impact in underdeveloped ones using the GMM method and an EKC framework for 93 countries. Also, they discovered that

Table 1 Quantitative descriptions of data

Variable	Description	Obs	Mean	S.D.	Min	Max
CO ₂	CO ₂ emissions in metric tons per capita	150	3.07	0.40	2.15	3.93
ICT	ICT composite index constructed by PCA with four variables: FTS, CPS, IU, and MHTE	150	-0.08	1.06	-6.39	1.85
NRE	Non-renewable energy use in quadrillion British thermal unit	150	-0.69	1.37	-3.21	1.93
FD	Financial development index	150	-0.89	0.21	-1.48	-0.55
GDP	GDP per capita in current US dollars	150	10.05	0.63	8.73	11.35
TO	Volume of trade as a ratio to GDP	150	4.60	0.29	3.77	5.26
EI	Energy intensity by population (MMBtu/person)	150	6.07	0.51	4.62	7.04

urbanization, income growth, energy use, and trade openness increased CO₂ emissions.

Using longitudinal data from 29 provinces from 2020 to 2010, Zhang and Liu (2015) looked into the consequence of ICT on CO₂ emissions in various regions of China. They showed that it helped China's CO₂ emissions decline. They used the gross value of “the Electronic and Information Manufacturing Industry” as a proxy for ICT. Anon Higon et al. (2017) examined the nonlinear connection between ICT and CO₂ emissions in 142 advanced and developing countries between 1995 and 2010 and found a reversed U-shaped affiliation. Asongu et al. (2018) utilized the GMM method to analyze data from 44 SSA countries between 2000 and 2012 and looked at how ICT affected the environment. Internet and cell phone users were used as a proxy for ICT, and it concluded that ICT harmed the atmosphere based on interactive regression. In contrast, non-interactive regressions showed no evidence of such a negative impact.

In the European Union (EU) nations, Park et al. (2018) considered the impact of internet use on CO₂ emissions using FD, economic growth, and trade as control variables. They used data from 2001 to 2014, the PMG estimator, and discovered that internet use increased CO₂ emissions, but FD enhanced environmental quality in the EU. Lu (2018) examined the effects of GDP growth, financial expansion, energy use, and ICT on CO₂ emissions using data from 12 Asian states from 1993 to 2013. The study used the ratio of Internet users per 100 individuals to represent ICT. It used the Common Correlated Mean Group estimation to show that, despite energy use, financial expansion, and income growth positively contributing to CO₂ emissions, the growing trend of ICT in Asian nations reduced CO₂ emissions. Using Tunisian data from 1975 to 2014, Amri et al. (2019) examined how ICT and total factor productivity affected environmental degradation. They used an ARDL paradigm to show that ICT had no impact on environmental pollution and, as a result, suggested expanding the ICT base.

Danish et al. (2019) used an EKC framework to estimate the effects of ICT and energy use on environmental contamination across various nations from 1990 to 2015. They employed the DOLS, FMOLS, and Driscoll-Kraay techniques, used fixed and mobile telephone subscribers separately as proxies for ICT, and discovered that ICT reduced CO₂ emissions levels in high- and middle-income nations, it increased emissions in low-income countries. Arshad et al. (2020) evaluated the impact of ICT on CO₂ emissions in 14 South and Southeast Asian countries from 1990 to 2014. They employed the PMG, DOLS, and FMLOS methodologies and used the total quantity of fixed and cellular phone subscribers per 100 persons as a proxy for ICT and concluded that ICT and FD degraded environmental quality in the region. The effect of ICT, FD, and institutional quality on environmental damage in Pakistan was studied by Godil

et al. (2020) using quarterly data from 1995Q1 to 2018Q4 and the quantile ARDL approach. According to the analysis, FD and ICT negatively impacted CO₂ emissions.

To investigate how ICTs and CO₂ emissions are related in 93 countries from 1995 to 2016, Alatas (2021) used three ICT proxies: internet users, fixed telephone subscriptions, and cell phone subscribers. The results indicated that ICT had a positive impact on pollutant emissions. In an EKC approach, Chien et al. (2021) used the Moments Quantile Regression technique to examine the effects of ICT [internet use] and financial progress on CO₂ emission in the BRICS countries. They found that ICT curtailed CO₂ emissions only at lower quintiles, while financial development increased emissions across all quintiles. To analyze how ICT affects CO₂ emissions in 58 emerging nations for data from 1990 to 2014, N'dri et al. (2021) used the total number of cellular and fixed phone subscribers per 100 persons as a proxy for ICT. Using the PMG model, they found that using ICTs was ecologically advantageous for low-income developing countries but not high-income developing economies.

Khan et al. (2022) used the generalized least square technique to analyze the effects of ICT on CO₂ emissions in BRICS countries from 1990 to 2019 and found that ICT had a negative impact on CO₂ emissions. Shehzad et al. (2022) used yearly data from 1976 to 2018 and the NARDL technique to investigate how ICT affects environmental quality, controlling energy use, and FD in Pakistan. They found that both “positive and negative shocks” of ICT negatively influenced CO₂ emissions, while energy consumption and FD worsened the air quality.

Ebaidalla & Abusin (2022) used MG and AMG approaches, utilized data from 1995 to 2018, and investigated how globalization and ICTs affected CO₂ emissions in the GCC nations. They demonstrated that the expansion of ICT enhanced CO₂ emissions and degraded the environment in GCC nations. The growth of ICT stimulated economic progress but at the cost of the environment.

The studies mentioned above examined the connection between ICT and CO₂ emissions utilizing various frameworks but came to no firm conclusions. Some showed a positive effect of ICT on CO₂ emissions, while others showed a negative consequence. Several estimation methods, including ARDL, NARDL, QARDL, and GMM approaches, were used in earlier investigations. Following a similar trend, we employ the panel NARDL method. The research mentioned above employed one or two ICT components—mobile subscription, fixed telephone subscription, and internet use—or, at best, an ICT index comprising these three elements—to define ICT. As a novelty, we generate a new ICT index by adding medium and high-tech exports as a fraction of all manufactured exports and the three components above. (1) We investigate the asymmetric influence of ICT on air pollution for the first time for GCC economies. As far as the

authors are aware, recent research (Ebaidallah and Abusin, 2022) considered the symmetric influence of ICT on pollutant emissions in the GCC nations. (2) This research attempts to add to the existing body of literature and examine the asymmetric consequence of ICT on CO₂ emissions in GCC nations following an EKC framework controlling energy use [non-renewable], energy intensity, trade, and FD employing the NARDL approach.

Data and methods

The study utilizes panel data from 1995 through 2019 on the GCC countries. The data on CO₂ emissions, ICT, GDP, and trade (openness) are obtained from the World Bank (2022). The ICT composite index is constructed based on the PCA comprising variables: FTS, CPS, IU, and MHTE, while FD data is obtained from the Financial Development (FD) index¹ of IMF (2022), and the energy consumption and its intensity data are sourced from EIA (2022). The data descriptions and their statistics are presented in Table 1. The values of all variables are taken as natural logarithms.

Model construction

Since the study considers the asymmetric impact of ICT on CO₂ emissions in an EKC framework in GCC nations, a model is formulated incorporating several control variables and presented in Equation 1.

$$CO_2 = f (ICT_{-pos}, ICT_{-neg}, GDP, GDPS, NRE, FD, TO, EI) \tag{1}$$

GDPS stands for squared GDP, while ICT_pos and ICT_neg indicate its positive and negative shocks and other variables are already defined in Table 1. ICT’s “positive and negative shocks” are attained using the partial sum technique described in Equations 2 and 3.

$$ICT_{pos}_t = \sum_{i=1}^t \Delta ICT_{pos}_i = \sum_i^t (\Delta \max(\Delta ICT_i, 0)) \tag{2}$$

$$ICT_{neg}_t = \sum_{i=1}^t \Delta ICT_{neg}_i = \sum_i^t (\Delta \max(\Delta ICT_i, 0)) \tag{3}$$

Before going for any empirical inquiry, we employ the cross-sectional dependency (CD) test Pesaran (2004) to identify whether the panel dataset is independent or mutually correlated. Suppose the panel is not independent but somewhat mutually interrelated. In that case, we apply the

second-generation unit root test (URT), namely, the CADF stationary test by Pesaran (2007) and CIPS stationary test by Pesaran et al. (2009), because conventional first-generation URT in the existence of cross-sectional dependency delivers inaccurate results. Moreover, we employ Karavias and Tzavalis (2014) and Ditzen et al. (2021) sequential URT to estimate stationarity under structural break and find any possible multiple breaks in the series.

The cointegration test developed by Westerlund (2007) is utilized in this study to decide whether there is any association among variables once the panel is stationary. This test accounts for slope heterogeneity in the panel and cross-sectional dependence. When the variables are cointegrated, this study employs the panel nonlinear ARDL (NARDL) estimation technique by Pesaran (1999) and Pesaran et al. (2001) to estimate both the long- and short-term asymmetric coefficients. The panel NARDL/ PMG assessment assumes the long-run parameters to be constant while allowing the short-run constants and error terms to diverge across the panel. Equation (4) shows how the PMG estimation takes a dynamic form.

$$\Delta CO_{2it} = \sum_{j=1}^{p-1} \theta_{ij} \Delta CO_{2it-j} + \sum_{j=0}^{q-1} \theta_{ij} \Delta X_{it-j} + \delta_i [CO_{2it-1} - \beta_i X_{it-1}] + \mu_i + \varepsilon_{it} \tag{4}$$

where $i = 1, 2, \dots, N$ (a total of all cross-sections), $t = 1, 2, 3, \dots, T$ (number of years), j indicates lag, X_i stands for explanatory variables’ vector, and δ_i is the coefficient for error correction term (ECT). ECT signifies the promptness of adjustment of CO₂ emissions to its long-run stability from any variation in X_i . A stable long-term association prevails if and only if $\delta_i < 0$.

The direction of causation among variables is finally determined using the “Dumitrescu-Hurlin (D-H) (2012)” panel causality check. In this assessment, all coefficients are expected to vary across various cross-sections. Equation 5 below gives a summary of the D-H model.

$$Y_{it} = \beta_i + \sum_{i=1}^k \alpha_i Y_{i,t-k} + \sum_{i=1}^k \delta_i X_{i,t-k} + \epsilon_{i,t} \tag{5}$$

Here, β_i represents the constant, α_i denotes the lag parameter, and δ_i signifies the coefficient slope. Equation 6 provides a clear definition of both the null and alternate hypotheses:

$$H_0 : \delta_i = 0, H_1 : \begin{cases} \delta_i = 0, \forall_i = 1, 2, \dots \dots \dots N \\ \delta_i \neq 0, \forall_i = N_1 + 1, N_1 + 2, \dots \dots N \end{cases} \tag{6}$$

All cross-sections reveal non-homogenous Granger causality, but the alternative proposition suggests that discovering at least one causal link is possible using the panel data.

¹ FD index ranks nations by their financial market access, depth, and efficiency.

Table 2 CD test outcomes

Test	d.f.	CO ₂	ICT	NRE	FD	GDP	TO	EI
Pesaran CD	15	-1.340	13.204*	17.951*	5.818*	17.911*	7.650*	-1.468

* $p < 0.01$

Results and discussion

CD test and panel URT results

The CD test outcomes in Table 2 show a mutual connectedness among the variables, indicating that the cross-sections are interrelated. Hence, conventional URT is not suitable for this study. Therefore, we conduct the CADF and CIPS as discussed, and their outcomes are exhibited in Table 3.

The panel URT results documented in Table 3 illustrate that the variables are stable at different levels [I(0) and I(1)]; mainly, the dependent variable is I(1). This makes it convenient to use the panel NARDL approach.

We apply Karavias and Tzavalis (2014) panel URT to trace any possible structural break; the outcome is exhibited in Table 4. The outcomes show that a break in CO₂ emissions [dependent variable] is unknown, while all explanatory variables have one break at different years and are stationary.

We further employ Ditzen et al. (2021) sequential URT to find multiple breaks at an unknown breakpoint, generating the outcome in Table 5.

The sequential test results for multiple breaks at an unknown breakpoint presented in Table 5 reveal that the test statistic magnitudes are lower than the Bai and Perron critical values at the 1% significance level. Thus, it evidences that the panel does not have a structural break for repeated breaks at an unknown breakpoint, and accordingly, we cannot estimate breakpoints.

Table 3 Panel URT results

Variable	CADF		CIPS	
	Level	1st diff	Level	1st diff
CO ₂	-1.754	-2.625**	-1.650	-3.618*
ICT	-2.971**	-4.952*	-2.161	-4.791*
NRE	-1.798	-2.976*	-1.775	-4.279*
FD	-3.088*	-3.912*	-2.820*	-4.931*
GDP	-2.554**	-2.433**	-1.587	-3.532*
TO	-2.037	-3.540*	-2.419**	-4.801*
EI	-2.036	-2.566**	-2.051	-4.108*

* $p < 0.01$ and ** $p < 0.05$

Test results for Westerlund cointegration

The outcomes of the Westerlund cointegration investigation based on lags(0 0), leads(0 0), Irwindow(0), constant trend, and bootstrap(1) are shown in Table 6. Since at the 1% level, the robust p values for the Gt, Ga, Pt, and Pa statistics are significant; the variables are cointegrated.

PMG assessment outcomes

The PMG model is defined as ARDL (1, 1, 1, 1, 1, 1, 1, 1) based on the NARDL approach, following the AIC criterion. The maximum number of dependent lags is three, and that of dynamic regressors is one, which AIC automatically determines. The estimated outcomes based on equation (4) are shown in Table 7.

Both ICT_{neg} and ICT_{pos} produce significant and negative coefficients, exerting a negative influence on environmental pollution, and thus, ICT is environment improving. Despite both shocks of ICT having negative coefficients, their magnitudes are different. A long-run asymmetry test is performed to verify their asymmetries and reported in the lower part of Table 7. The outcome shows that coefficients [C (1) ≠ C (2)] are not the same, and there is a long-run asymmetry between the coefficients of two ICT shocks, and the outcome reveals a long-run conducive asymmetric influence of ICT on the region’s environmental quality. These results are in line with Al-Mulali et al. (2015), Zhang and Liu (2015), Danish et al. (2018a), Danish et al. (2019), Godil et al. (2020), Chien et al. (2021), N’dri et al. (2021), Khan et al. (2022), and Shehzad et al. (2022) who argued that ICT helped bring about a gradual decline in environmental pollution. However, the results contradict the findings of Asongu et al. (2018), Park et al. (2018), Lu (2018), Arshad et al. (2020), Alatas (2021), and Ebaidalla & Abusin (2022), who found that ICT had a deleterious effect on environmental quality. This result has implications for the policymakers to enhance ICT initiatives and streamline the existing ICT policies to combat environmental pollution. It also follows that financial organizations and governments might be ICT-friendly and support ICT initiatives that benefit the environment.

LnGDP produces a significant and positive coefficient, while LnGDPS produces a negative and significant coefficient. It follows that a rise in GDP per capita income causes pollution to increase, while squared GDP per capita reduces

Table 4 URT results with a structural break

	CO ₂	ICT	GDP	FD	NRE	TO	EI
Estimated breakpoint	unknown	1999	1997	2017	1997	1997	2012
Statistic	-1.517	-8.360	-6.034	-5.044	-4.359	-3.757	-3.373
Bootstrap critical-value	-1.536	0.269	3.084	1.876	1.916	0.476	0.080
p-value	1.0000	0.000*	0.000*	0.000*	0.000*	0.000*	0.000*

* $p < 0.01$

it. Thus, a reversed U-shaped relation between “pollution and income growth” is established. This is the notion of the EKC theory, and the findings of this study validate it. It means that as the GCC economies continue to expand, people can enjoy a higher standard of life due to better access to improved healthcare and more stringent regulations to ensure product quality and environmental pollution is lessened by these steps. The outcomes are consistent with the EKC theory and those found in many previous pieces of research, such as Al-Mulali et al. (2015), Armeanu et al. (2018), Gokmenoglu & Taspinar (2018), Beyene & Kotosz (2020), Chien et al. (2021), and Islam (2021). The outcome suggests that economic growth is necessary and a prerequisite for the GCC countries to maintain a higher standard of living and safeguard the environment.

The constant of LnNRE is positive and significant, indicating an affirmative long-run connection with CO₂ emissions. A 1% escalation in energy use causes a 0.11% growth in CO₂ emissions. The use of non-renewable energy generates a considerable long-term influence on environmental pollution in the GCC nations. The outcome is usual and in conformity with literature including Jalil and Feridun (2011), Shahbaz et al. (2014), Manuel et al. (2016), Javid and Sharif (2016), Armeanu et al. (2018), Rahman et al. (2019), Jaruwat (2020), Salari et al. (2021), Islam (2021), Jiang, et al. (2022), and Adeleye et al. (2023). The finding points the policymakers to explore and enhance renewable green energy sources, enhance their consumption, and reduce the use of traditional energy in economic events to limit pollution.

LnFD makes a significant and negative constant, revealing that existing financial development and practices in the GCC region exert a considerable negative impact on environmental degradation, meaning that it has a favorable effect

on the environment. A 1% rise in the FD index results in a 0.22% drop in CO₂ emissions. Thus, the financial organizations in the GCC countries seem to be congenial in financing initiatives that benefit the environment. In a similar vein, a rise in the magnitude of the FD index may help to lessen the amount of pollution in the environment. Thus, financial development in the region has been conducive to pollution control. The finding is in line with Tamazian et al. (2009) and Jalil and Feridun (2011), Li et al. (2015), Abbasi & Riaz (2016), who highlighted its negative impact on the latter, while opposes Zhang (2011), Javid and Sharif (2016), Khan et al. (2019), Islam (2022a), and Islam (2022b), who reported positive impact of FD on environmental pollution. The result offers implications for managers in the financial organization to devise innovative ICT-based financial development to combat CO₂ emissions and ensure a sustainable environment.

The coefficient of LnTO is also affirmative and significant, which follows that trade openness exerts much pressure on CO₂ emissions in the long run. The GCC countries' reliance on trade has been relatively high, and much of their economic activities is supported by trade. As a result, it generates a positive impact on environmental pollution. This finding confirms the previous outcomes of Shahbaz et al. (2014), Zhang (2018), Tachie et al. (2020), and Appiah et al. (2022), who revealed a significant positive impact of trade on pollution. However, our finding is dissimilar to that of Yu et al. (2019), who reported a negative influence on CO₂ emissions; Javid and Sharif (2016) and Zhang (2021) found no impact of trade on the latter. The finding has implications for how trade policies should be created and how trade can be facilitated by giving consumers less-emission-producing products and services and cheering the use of environmentally conscious technologies.

Table 5 Sequential URT for several breaks at unknown breakpoints

	Test statistic	Bai and Perron critical values		
		1% level	5% level	10% level
F(10)	1.54	3.56	2.96	2.68
F(21)	-0.50	3.71	3.22	2.95
F(32)	-2.17	3.83	3.35	3.09
F(43)	-4.11	3.88	3.46	3.20

Table 6 Cointegration test outcome

	Gt	Ga	Pt	Pa
Value	-3.328	-6.543	-7.388	-5.896
p value	0.340	1.000	0.439	0.999
Robust p value	0.000*	0.000*	0.000*	0.000*

* $p < 0.01$

Table 7 Panel NARDL/PMG outcomes

Var.	Coeff.	Std. err.	t-stat.	p value
Long run equation				
LnICT_neg	-0.155	0.021	-7.438	0.000*
LnICT_pos	-0.096	0.026	-3.749	0.000*
LnGDP	2.677	0.509	5.263	0.000*
LnGDPS	-0.134	0.025	-5.401	0.000*
LnNRE	0.107	0.027	3.985	0.000*
LnFD	-0.221	0.046	-4.808	0.000*
LnTO	0.134	0.061	2.199	0.031**
LnEI	0.481	0.066	7.251	0.000*
Short run equation				
ECT	-0.478	0.208	-2.293	0.025**
$\Delta(\text{LnICT}_{\text{pos}})$	-0.033	0.038	-0.857	0.394
$\Delta(\text{LnICT}_{\text{neg}})$	0.050	0.012	4.128	0.000*
$\Delta(\text{LnGDP})$	-2.542	2.020	-1.259	0.212
$\Delta(\text{LnGDPS})$	0.129	0.103	1.256	0.213
$\Delta(\text{LnNRE})$	-0.006	0.061	-0.098	0.922
$\Delta(\text{LnFD})$	0.141	0.064	2.214	0.030**
$\Delta(\text{LnTO})$	-0.039	0.030	-1.323	0.190
$\Delta(\text{LnEI})$	0.203	0.180	1.126	0.264
C	-6.567	2.892	-2.271	0.026**
Long-term asymmetry test result				
Test stat.	Value	d.f.	p value	
t-stat.	2.131	128	0.035**	
F-stat.	4.539	(1, 128)	0.035**	
Chi-square	4.539	1	0.033**	
H ₀ : C (1) = C (2); H ₁ : C (1) ≠ C (2)				

*p<0.01 and **p<0.051

The constant of LnEI is positive and significant, indicating its long-term positive impression on CO₂

emissions. Since the GCC nations are bestowed with plenty of non-renewable energy sources, their economic operations are sustained by conventional energies. Consequently, their energy use and intensity are relatively high, eventually causing environmental damage. The outcome conforms with those by Dogan and Shah (2021), Danish et al. (2022), and Shokoohi et al. (2022), who found its adverse consequence on the environment. The result points to the need for the government to develop new initiatives, investment possibilities, and economic incentives in support of renewable energy and energy-saving devices and technology.

In addition, the short-run dynamics demonstrate that ICT_neg and FD increase CO₂ emissions while other variables' impact remains insignificant. The ECT constant is negative [-0.478] and statistically significant, indicating a long-run cointegration among variables and a speed of adjustment at the rate of 47.8% per year to long-term equilibrium.

D-H causality check

The D-H causality outcomes are portrayed in Table 8, which generates several bidirectional and unidirectional causal linkages. Still, we demonstrate only the main eight causalities to check the robustness of the NARDL estimates. The first bidirectional causality exists between ICT_neg ↔ LnCO₂; the second feedback association occurs between ICT_pos ↔ LnCO₂; the third causation happens from LnGDP→LnCO₂; the fourth one-way causality lies from LnGDPS→LnCO₂; the fifth two-way causation exists between LnNRE ↔ LnCO₂; the sixth one-way causation runs from LnFD→LnCO₂; the seventh causality occurs

Table 8 Pairwise D-H causality outcomes, Lags: 2

	Null hypothesis	W-stat.	Zbar-stat.	p value	Decision
1	LnICT_neg does not cause LnCO ₂	6.982	4.456	0.000	LnICT_neg↔LnCO ₂ bidirectional
	LnCO ₂ does not cause LnICT_neg	4.244	1.869	0.062	
2	LnICT_pos does not cause LnCO ₂	5.473	3.030	0.002	LnICT_peg↔LnCO ₂ bidirectional
	LnCO ₂ does not cause LnICT_pos	5.317	2.882	0.004	
3	LnGDP does not cause LnCO ₂	7.241	4.792	0.000	LnGDP→LnCO ₂ unidirectional
	LnCO ₂ does not cause LnGDP	3.042	0.760	0.447	
4	LnGDPS does not cause LnCO ₂	7.096	4.652	0.000	LnGDPS→LnCO ₂ unidirectional
	LnCO ₂ does not cause LnGDPS	3.146	0.860	0.390	
5	LnNRE does not cause LnCO ₂	4.564	2.222	0.026	LnNRE↔LnCO ₂ bidirectional
	LnCO ₂ does not cause LnNRE	5.063	2.701	0.007	
6	LnFD does not cause LnCO ₂	5.571	3.188	0.001	LnFD→LnCO ₂ unidirectional
	LnCO ₂ does not cause LnFD	2.697	0.429	0.668	
7	LnTO does not cause LnCO ₂	9.851	7.298	0.000	LnTO↔LnCO ₂ bidirectional
	LnCO ₂ does not cause LnTO	4.114	1.790	0.074	
8	LnEI does not cause LnCO ₂	4.218	1.890	0.059	LnEI↔LnCO ₂ bidirectional
	LnCO ₂ does not cause LnEI	4.684	2.337	0.019	

between $\text{LnTO} \leftrightarrow \text{LnCO}_2$; and the eighth bi-directional causality happens between $\text{LnEI} \leftrightarrow \text{LnCO}_2$.

The presented outcomes of the causality check acknowledge the NARDL findings and validate their robustness.

Conclusion

The research has investigated the impact, both “positive and negative shocks,” of ICT on CO_2 emissions, controlling energy use, financial progress, openness to trade, and energy intensity employing the EKC framework for the GCC countries. The Westerlund cointegration assessment reveals a cointegrating association among variables. The nonlinear ADRL approach based on the PMG estimate divulges ICT asymmetrically improves the environment; squared GDP and FD also have a similar effect. In contrast, in the long run, non-renewable energy, trade, GDP, and energy intensity damage the latter. It follows that the policymakers of the GCC nations should strengthen their ICT initiatives and streamline the existing ICT policies to combat environmental pollution. They may coordinate with financial organizations to support ICT initiatives that benefit the environment.

The GCC nations mainly generate and use non-renewable energies and less renewable fuels, which invariably emit much CO_2 . It is impractical to minimize energy as it will have a significant negative impact on their economic growth and development. Moreover, since these nations are surplus energy producers, their energy intensity has been relatively high and ultimately negatively impacts the environment. Hence, policymakers need to invest in renewable and green energy sources, motivate the private sector through incentives to invest in green energy and energy-saving products and technology, and raise their production and consumption and thereby reduce the use of traditional energy for economic purposes to limit pollution.

The outcome further exhibits that financial sector growth has been conducive to the environment in the region, which might have helped the existing ICT infrastructure and facilities to promote the environment. Therefore, the GCC policymakers should focus on devising innovative ICT-based financial development to limit CO_2 emissions and ensure a sustainable environment. Financial institutions may provide credits to businesses and stockholders to implement environmentally friendly initiatives. The outcome further validates the EKC notion and demonstrates a reversed U-shaped association between atmospheric pollution and income. Thus, economic growth is indispensable and a precondition for the GCC countries. Moreover, the panel causality test shows that energy use, income growth, squared GDP, trade openness, and energy

intensity cause CO_2 emissions, thus validating the NARDL findings’ conclusions.

Our findings lead us to recommend that the GCC countries may invest in ICT activities and strengthen ICT policies that will result in energy efficiency, which has the potential to lessen the adverse environmental effects of economic expansion and energy consumption. They should invest in renewable and green energy production, rationalize non-renewable energy use, regulate financial institutions towards environmental green financing, and rationalize trade policies to produce less emitting products. The GCC governments should also improve cooperation among them to coordinate their ICT policy, energy policy, and growth strategy to minimize environmental impacts.

Author contributions Each author contributes equally. *Sk Habibur Rahaman* performed material preparation, data collection, and analysis, while *Md. Saiful Islam* did the study conception, design, and drafting.

Data availability Data is taken from the following two websites: <https://databank.worldbank.org/source/world-development-indicators#>, <https://www.eia.gov/international/overview/world>, and <https://data.imf.org/?sk=388DFA60-1D26-4ADE-B505-A05A558D9A42&sid=1479329334655>.

Declarations

Ethics approval and consent to participate Not applicable.

Consent for publication Not applicable.

Competing interests The authors declare no competing interests.

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