



# Renewable energy for achieving environmental sustainability: institutional quality and information and communication technologies as moderating factors

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Received: 8 April 2022 / Accepted: 6 May 2023 / Published online: 25 May 2023  
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## Abstract

The environmental challenges are currently placed at the forefront in order to achieve sustainable development. Although existing studies have largely examined the underlying factors of the environmental sustainability, the institutional quality and the role of information and communication technologies (ICTs) still insufficiently investigated. The aim of this paper is to clarify the role played by institutional quality and ICTs to mitigate environmental degradation at different scales of the ecological gap. Therefore, the purpose of the study is to examine whether the quality of institutions and ICTs consolidate the contribution of renewable energy to reduce the ecological gap and thereby, promote environmental sustainability. The results of panel quantile regression applied to fourteen selected Middle East (ME) and Commonwealth of Independent States (CIS) countries from 1984 to 2017 showed that the rule of law, control of corruption, Internet use, and mobile use exert no beneficial effects on environmental sustainability. The ICTs and the institutional development through the presence of an appropriate regulatory framework and the control of corruption have rather advantageous moderating effects on the environmental quality. Indeed, our findings revealed that the effects of renewable energy consumption on the environmental sustainability are positively moderated by the control of corruption, Internet use, and mobile use for countries with medium and high ecological gaps. The beneficial ecological effects of renewable energy are also moderated by the presence of a solid regulatory framework, but only for countries with high ecological gaps. In addition, our results showed that financial development promotes environmental sustainability in countries with low ecological gaps. Urbanization has perverse effects on the environment across all quantiles. The results found lead to important practical implications for preserving the environment as it suggests designing ICTs and improving the quality of institutions oriented to renewable energy sector in order to reduce the ecological gap. In addition, the findings from this paper can serve decision-makers in terms of environmental sustainability given the globalizing and conditional approach followed.

**Keywords** Ecological gap · Renewable energy · Institutional quality · Information and communication technologies

## Highlights

- The moderating effects of the quality of institutions and ICTs in the renewable energy-environmental sustainability nexus were investigated.
- Renewable energy- environmental sustainability nexus differs according to the ecological gap.
- The ecological effects of renewable energy consumption are conditioned by institutional quality and ICTs.
- Medium and high ecological gap can be reduced by promoting renewable energy through the moderating effects of corruption control, Internet use, and mobile use.
- The rule of law reduces high ecological gap if it is intended for the renewable energy sector.

Responsible Editor: Roula Inglesi-Lotz

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## Introduction

Favourable ecological conditions have become, due to the global warming, an essential pillar of sustainable development (Ulucak et al., 2019). To this end, the renewable energy sector is considered as an important lever leading to environmental sustainability. Numerous studies have investigated the role that renewable energy consumption plays in reducing CO<sub>2</sub> emissions (Bekhet et al., 2017; Shahzad et al. 2017; Charfeddine and Kahia, 2019) or greenhouse gases (Khan et al., 2017). However, given the restrictive approach followed by the majority of existing studies focusing on a single dimension of the environment, principally air pollution, a recent research thread has opted for the ecological footprint

as an indicator of environmental degradation. Among the existing studies that have retained the ecological footprint as a proxy for environmental quality, few have incorporated renewable energy as an underlying factor. Most of the previous research has been limited to examining only the effects of non-renewable energy on the ecological footprint and exclude renewable energy consumption from their analysis. According to Ulucak and Apergis (2018) and Danish et al. (2019), the use of CO<sub>2</sub> emissions is not suitable to analyse the environmental deterioration since other dimensions of the environment are excluded such as mining, oil, soil, and forests. The ecological footprint is reliable, comprehensive, and useful measure of environmental sustainability and exhaustively reflects the effects of human activity on nature and the natural resources actually used in society (Wackernagel and Rees, 1998; Bilgili & Ulucak, 2018; Solarin and Bello, 2018). As a result, the ecological footprint appears as more globalizing, which incorporates six components, namely grazing land, build-up land, forest land, cropland, and carbon footprint. All these components reflect exploitable bio-productive lands (Nathaniel and Khan, 2020). In fact, two important aspects have experienced a remarkable boom in recent decades, namely the institutional development and the expansion of big data under the effect of the digital network dispersion. The ability of decision-makers to implement the most adequate policies in order to protect the environment against pollution and the abuse of the exploitation of natural resources depends on the nature of institutions and the ecological footprint mitigated or generated by information and communication technologies (ICTs). Few existing studies (Damania et al., 2004; Wright, 2007; Culas, 2007) have focused on globalizing indicators measuring environmental sustainability to analyse the institutional quality-environmental degradation nexus. Most of the previous research has focused on air pollution indicators such as CO<sub>2</sub>, NO<sub>2</sub>, phosphorus, and suspended particulate concentrations and suspended solids (Cole, 2007; Castiglione et al., 2013; Abid, 2016; Bhattacharya et al., 2017; Danish and Ulucak, 2020). This is why the results found in the literature on institutional quality-environmental quality nexus have not led to a common consensus yet. Moreover, in this era of digital expansion, the question relating to the ecological effects of ICTs such as the Internet and mobile phones is of increased importance to achieve the sustainable development goals and limit global warming (Zhou et al., 2019). This field of research is particularly important, given that the ICT sector contributes to around 2% of global emissions (IEA, 2019). Despite this importance of ICTs, few existing research has examined their effects on the ecological gap. The majority of studies have focused on the impact of digitalization on CO<sub>2</sub> emissions (Wan Lee and Brahmastre, 2014; Zhang and Liu, 2015; Salahuddin et al., 2016; Ozcan and Apergis, 2017; Faisal et al., 2020; Halder and Sethi, 2022).

This study makes it possible to overcome the shortcomings of the existing literature and presents some contributions, which are summarized as follows: First, little research has analysed the conditional effects of renewable energy on environmental degradation by including the moderating effects of institutional quality and ICTs. Several studies integrated the interaction term of ICTs with some others factors (Moyer and Hughes, 2012; Ahmed et al. 2017; Asongou, 2018; Khan et al., 2018; Chen et al., 2019; Danish, 2019; Khattak et al., 2020; Avom et al., 2020) to examine its effects on the environmental degradation. Few studies (Halder and Sethi, 2022) have investigated the fallouts of the interaction between ICTs with renewable energy on environmental degradation. We consider that the integration in our model of this last interaction makes it possible to discover the effects of green ICT (Suryawanshi and Narkhede, 2014) on environmental sustainability. Therefore, the findings of this research can provide clarifications on the moderating role played by ICTs and the quality of institutions as two channels facilitating the exploitation of the clean energy sector in order to mitigate environmental degradation. Second, most of the literature has been devoted to the analysis of the effects of ICTs or institutional quality on CO<sub>2</sub> emissions. Little attention is given to the impact of Internet use, mobile use, and institutions on the ecological footprint and biocapacity, and therefore, on the ecological gap as more exhaustive and globalizing indicator. This study is part of the literature on the nexus between renewable energy and environmental sustainability but stressing that the ecological gap is a more reliable indicator of environmental pressures and ecological performance. Finally, the present research focused on the Middle East (ME) and Commonwealth of Independent States (CIS) countries and few existing studies have used this sample to address the questions posed with regard to the role played by the quality of institutions and ICTs in reducing the ecological gap. In this regard, ME countries have experienced adverse environmental conditions as a result of global warming and urban development. The ME countries have approximately 370 million inhabitants spread over seven million square kilometres which trace the pressures exerted by urbanization on the environment (Mohammadi et al., 2022). According to International Monetary Fund (IMF, 2022), climate conditions in ME and central Asia countries have experienced unprecedented temperature rises over the past decades, huge natural disasters, and abnormal rainfall. Despite geological and natural assets (Ostovari et al., 2022), ME countries next to CIS countries are more likely to ensure environmental sustainability than other countries in the world. Based on this fact, this study aims to examine whether institutional development and ICTs can constitute a means of resilience against accentuated global warming in ME and CIS countries by ensuring environmental sustainability.

The present study responds to these limits by first analysing the repercussions of renewable energy consumption on the ecological gap and not on a single dimension of environmental quality. In this study, we examine the role played by institutional quality and ICTs to enhance the environmental sustainability and to moderate and condition the effects of renewable energy on the ecological gap. The results of the study showed that ICTs and the quality of institutions remain unable to overcome environmental damage in the case of ME and CIS countries. In addition, the study revealed that the moderating role of Internet use, mobile use, rule of law, and control of corruption in the relationship between renewable energy consumption and environmental sustainability depends on the level of the ecological gap.

The rest of the paper is organized as follows: First, we present the existing studies on the effects of renewable energy, institutional quality, and ICTs on the quality of the environment. Then, we explain the methodology followed in particular the data used and the models retained. Finally, we present the empirical results found and the discussion as well as the main implications.

## Literature review

### Renewable energy and ecological gap

Findings concerning the effects of renewable energy on ecological footprint are inconclusive. A recent line of research highlighted the negative effects of renewable energy on the ecological footprint (Destek et al., 2018; Alola et al., 2019; Wang and Dong, 2019; Danish et al. 2020; Destek and Sinha, 2020; Sharif et al., 2020), while others (Nathaniel et Khan, 2020) reported insignificant effects. Bello et al. (2018) found that the hydroelectricity reduces ecological footprint and reported an inverted U-shaped relationship between economic growth and ecological footprint. Wang and Dong (2019) focused on the causal relationship between a set of variables which are renewable and non-renewable energy, urbanization, economic growth, and ecological footprint in the case of 14 SSA countries. These authors discovered that a significant bidirectional link is confirmed between urbanization, non-renewable energy, economic growth, and ecological footprint. Moreover, their findings indicated that environmental degradation is reduced under the effect of renewable energy sources unlike non-renewable energy consumption. Destek and Sinha (2020) also consolidated the negative effects of renewable energy and the positive repercussions of non-renewable energy consumption on ecological footprint in the case of 24 OECD countries spanning the period 1980–2014. Based on FMOLS and DOLS techniques, empirical findings of Danish et al.

(2020) indicate that renewable energy decreases ecological footprint as for the effects exerted by natural resource rent and urbanization in the case of BRICS countries during the period 1992–2016. The ability of renewable energy consumption to overcome the ecological footprint in the long-run was also supported by Khan et al. (2021) by applying a GMM, GLM methods, and robust least-squares. The findings of this study revealed that population growth and non-renewable energy consumption lead to environmental degradation. Sharif et al. (2020) referred to the quantile ARDL technique in order to analyse the relationship between renewable and non-renewable energy on the ecological footprint in the case Turkey spanning the period 1965Q1–2017Q4. Their results reported that for each quantile, renewable energy exerts a beneficial impact on the ecological footprint. The empirical results of Usman et al. (2020) using ARDL model and Toda-Yamamoto causality test during the period 1985Q1 to 2014Q4 showed the negative effects of renewable energy on environmental quality based on ecological footprint in the case of the USA. Conversely, the ecological footprint is amplified by economic growth and biocapacity. Based on a sample of 128 countries with different levels of incomes, and by applying the regression analysis, Ali et al. (2021) confirmed that for all panels retained, there is a reduction in the ecological footprint due to an increase in renewable energy. By applying the AMG method in the case of 15 highest emitting countries from 1990 to 2017, Usman et al. (2021) supported the beneficial fallout of renewable energy, as well as trade openness and financial development on the environmental quality. The findings of Nathaniel et al. (2021) based on Common Correlated Effects Mean Group (CCEMG) and Pool Mean Group (PMG) showed that natural resource worsens environmental degradation, while renewable energy overcomes ecological footprint. According to these authors, human capital has not yet reached its desired level to mitigate ecological footprint in the BRICS countries. In the light of the above ideas and the results of existing studies, the present research aims to test the following central hypothesis:

H.1: Renewable energy consumption reduces the ecological gap.

The positive contribution of the renewable energy sector to reduce the ecological footprint is not the only possible configuration. Indeed, the study of Nathaniel and Khan (2020) examined the impact of renewable and non-renewable energy consumption alongside economic growth, and urbanization on ecological footprint from 1990 to 2016 in 6 selected ASEAN countries. Their results reported that renewable energy exerts insignificant effect on ecological footprint while economic growth and non-renewable energy consumption damage the environment

## Institutional quality and environmental sustainability

The role that institutions can play in environmental protection is still under-investigated. Indeed, environmental sustainability is considered as a public good that requires government intervention. However, the private sector underestimates the real costs of environmental degradation, particularly pollution, under the effect of the externalities it generates. Therefore, governments often fail to implement the political institutions and regulatory framework that can reduce the excessive exploitation of natural resources and environmental pollution. The corrupt practices lead to misallocation of public funds and take various forms such as laws condoning the abuse of natural resource exploitation, bribery to pass deals, and lacklustre environmental norms demotivating environmental sustainability (Sinha et al., 2019). All these illegal acts overwhelm the transition to green innovation, especially when combined with the bureaucracy that characterizes countries without a developed institutional framework. So, a solid and transparent regulatory framework can eradicate corruption and establish a better allocation of public finances, which in turn exerts a positive impact on society and the environment. Although the effects of institutional quality on environmental degradation are still debatable, little research has investigated institutions-environment mitigation nexus. The most existing studies on the impact of institutions on environmental degradation have led to negative effects (Castiglione et al., 2013; Abid, 2016; Bhattacharya et al., 2017; Rizk, 2018; Danish et Ulucak, 2020). By focusing on the importance of the soundness of the regulatory framework in the protection of the environment, Culas (2007) underlines that the level of deforestation is weakened through the enforceability of contracts imposed by governments. For their part, Castiglione et al. (2013) highlighted that the inflection point of the Environment Kuznet Curve is set at a lower threshold of per capita income and, therefore a greater ability to decline CO<sub>2</sub> emissions as the rule of law is solid. Based on the GMM dynamic model applied to SSA countries from 1996 to 2010, Abid (2016) showed the importance of institutions to mitigate the pollution. The findings of Rizk (2018) based on Three-Stage Least Squares method applied in 146 countries spanning the period 1996–2014 showed that the environment is preserved under high institutional quality. From their side, Bhattacharya et al. (2017) confirmed the beneficial effects of institutions to decline CO<sub>2</sub> emissions across regions by using FMOLS and system GMM and by referring to 85 developed and developing economies. Sarkodie and Adams (2018) highlighted the importance of political institutions to reduce the climate change in South Africa, and they applied the ARDL method spanning the period 1991–2016 to justify these results. Danish

and Ulucak (2020) investigated the impact of institutional arrangements on the environment in the case of the 18 APEC countries from 1992 to 2015 and their findings support the presence of a unidirectional causal relationship ranging from the institutional quality to the emissions of carbon. In addition, their empirical analysis indicated that environmental protection is achieved by high institutional quality without requiring high economic growth. This study aims not only to examine the direct effects of the institutional quality on the environmental sustainability, but also its moderating effects. Therefore, the present research attempts to examine the following second hypothesis:

H.2: The effects of the renewable energy consumption on the environmental sustainability are moderated by the institutional quality.

However, several other studies consider that better institutional quality is not always beneficial. Cole (2007) highlighted that the indirect effect is more remarkable in countries with high income. In addition, this author reported that corruption has a negative effect on the environment by generating more CO<sub>2</sub> and sulphur dioxide emissions. According to Welsch (2004), corruption affects pollution, either directly by implementing more severe laws or indirectly via its impact on per capita income, which generates more pollution. This author found that an increase in the level of corruption generates more pollution in terms of CO<sub>2</sub>, NO<sub>2</sub>, phosphorus, and suspended particulate concentrations and suspended solids. Moreover, the control of corruption not only affects greenhouse emissions, but its impact can be multidimensional. In this regard, Fredriksson et al. (2005) discovered that energy waste positively affected by corruption made possible through more lax regulations. Pellegrini and Gerlagh (2006) counteracted these findings and concluded that the environmental protection index is inversely related to corruption perception. Other studies followed a more aggregated approach by examining the effects of corruption on environmental sustainability. The evidence found by Damania et al. (2004) and Wright (2007) is that the rise of corruption decreases sustainability and biodiversity. In the light of previous studies, it appears that the majority of the existing studies have focused on air pollution and neglects other dimensions resulting from human activity on nature. It is therefore interesting for us to deal with the effects of institutional quality on the ecological gap in general to enlighten decision-makers in terms of the procedures to be emphasized.

## ICTs and environmental sustainability

The prevalence of ICTs in all areas of the economy and in many sectors of activity such as energy, logistics, agriculture, and electricity has prompted many researchers to investigate the ICT-environmental degradation nexus. The



predominance of the service sector, bolstered more particularly by the expansion of ICTs, can in turn affect the environment differently (Salahuddin et al., 2016). In fact, the impact of ICTs on the environment is assessed from two perspectives, which are energy efficiency and energy demand. According to Lennerfors (2015), the establishment of innovation processes based on mechanization, energy savings, new transport mechanisms, and smart cities is beneficial in reducing CO<sub>2</sub> emissions. In addition, ICTs are considered as a lever to minimize the primary energy consumption and therefore, provide more energy efficiency, and eco-friendly fabrication in highly polluting sectors, by establishing new smart methods (Fagas et al., 2017; Abbasi & Riaz, 2016). The control and management of electricity grids, substitution of polluting energy by renewable energy, e-commerce, dematerialization, decarbonization, and the proliferation of data all constitute channels through which ICTs generate greater energy efficiency. As advocated by Malmudin and Lunden (2018), the application of ICTs in the renewable energy sector can take on several configurations via its indirect effects on the fields of buildings, logistics and transport, manufacturing, and non-manufacturing industries. In this context, ICTs provide energy efficiency and smart applications and programs capable of promoting innovation in new areas of clean energy. Among the smart applications are more particularly smart meters, grids, and logistics favouring the decentralization of energy production.

On the other side, the availability and the rise of ICTs have caused a growing demand for energy and other goods, which becomes easily accessible and hence, generating more waste and pollution (IEA, 2017; Wei and Liu, 2017; Park et al., 2018; Shabani et al., 2019). The literature on the relationship between ICTs and environmental degradation is divided into two main avenues: A first line of research postulates that the Internet use and mobile use as a form of ICTs decline CO<sub>2</sub> emissions (Haseeb et al., 2019; Ozcan and Apergis, 2017; Al-Mulali et al., 2015,b; Zhang and Liu, 2015). The second line of research rather reported the harmful effects of ICTs on the environment in general, and particularly on CO<sub>2</sub> emissions (Wan Lee and Brahmaresne, 2014; Salahuddin et al., 2016). The negative impact of ICTs on carbon emissions has been confirmed by several studies in many regions, whatever the European Union countries (Park et al., 2018), African countries (Asongu, 2018), and Asian countries (Wan Lee and Brahmaresne, 2014; Sharma et al., 2021). The results of dynamic seemingly unrelated regression used by Haseeb et al. (2019) indicated that ICT significantly reduces CO<sub>2</sub> in the case of BRICS countries spanning the period 1994–2014. By focusing on a panel of emerging countries, Danish et al. (2018) showed that ICTs have perverse effects on the environment by generating more CO<sub>2</sub> emissions, but

these effects become beneficial with increasing income. Higon et al. (2017) partially validated these findings and found that the environmental Kuznets curve (EKC) relationship between ICT and CO<sub>2</sub> is confirmed. In addition, these authors showed that the ability of ICTs to reduce CO<sub>2</sub> emissions could only be achieved in the presence of a certain level of income. To highlight the negative repercussions of the use of ICTs on CO<sub>2</sub> emissions, other studies adopted a sectoral approach in the case of China (Zhou et al., 2019) and Iran (Dehghan et al., 2019). Danish (2019) examined ICT-CO<sub>2</sub> emissions nexus by distinguishing between high-, middle-, and low-income countries. This author showed, by applying FMOLS, DOLS, and Driscoll-Kraay regression techniques, that the positive effects of ICTs on CO<sub>2</sub> emissions are only confirmed in the case of low-income countries unlike middle- and high-income countries in which these effects are rather negative. For their part, Faisal et al. (2020) found that the effects of ICTs on carbon emissions are inverted-U shaped in the case of fast-emerging economies during the period 1993–2014. Besides the above-mentioned approaches, other studies have carried out a more detailed analysis showing that the articulation between ICTs and environmental pollution is contingent upon a number of other variables. Some research has examined the environmental repercussions of interactive terms between ICTs and economic growth and financial development (Khan et al., 2018), foreign direct investment and international trade (Danish, 2019), innovation (Halder and Sethi, 2022), and globalization (Asongou, 2018; Ulucak et Khan, 2020). Along with this literature, a set of other research reported that the effects of ICTs on the environmental quality are conditioned by renewable energy (Moyer and Hughes, 2012; Ahmed et al. 2017; Khattak et al., 2020; Chen et al., 2019; Avom et al., 2020). The results of Bootstrapped Panel-Quantile regression followed by Halder and Sethi (2022) indicated that the Internet use and the renewable energy consumption are beneficial for declining CO<sub>2</sub> emissions across all quantiles in the case of 16 emerging countries spanning the period 2000–2018. Their findings revealed that the renewable energy consumption conditions the effect of mobile use on CO<sub>2</sub> emissions, but it has no moderating role in the relationship between Internet-penetration and CO<sub>2</sub> emissions. It emerges from an overview of the existing literature that pollution was considered as the dominant dimension in the analysis of the nexus between ICTs and environmental degradation. In this study, we investigate whether ICTs are at the service of renewable energy to improve environmental sustainability by referring to the ecological gap as an indicator. Based on this idea, the present research aims to examine the following third central hypothesis:

H.2: The effects of the renewable energy consumption on the environmental sustainability are moderated by the information and communication technologies.

In the light of the above-mentioned ideas, the conceptual model integrating all the aforementioned hypotheses is described by Fig. 1.

## Methodology

### Data

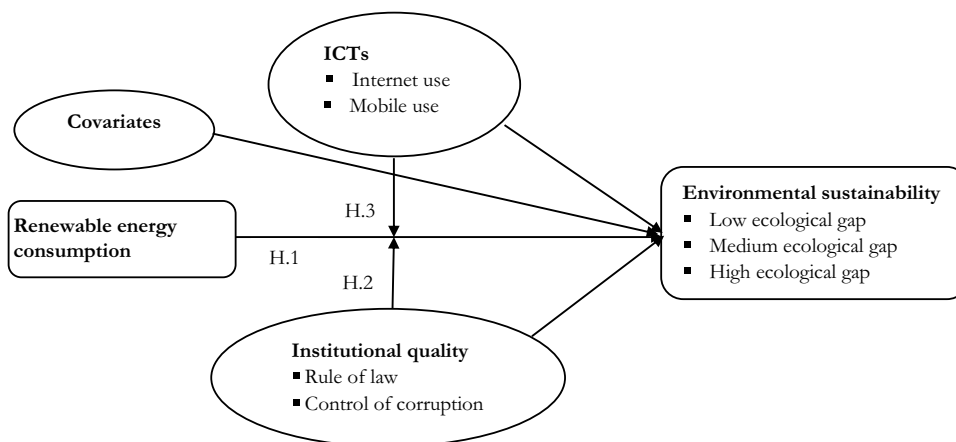
Our study is applied to the case of fourteen Middle East and Commonwealth of Independent States countries. We have specifically retained six countries from the Middle East region, which are Iran, Jordan, Lebanon, Oman, Saudi Arabia, and United Arab Emirates, and eight countries which acquired their independence following the collapse of the Soviet Union in 1991, namely Armenia, Georgia, Kazakhstan, Kyrgyzstan, Russia, Tajikistan, Ukraine,

and Uzbekistan. Some countries belonging to these two regions were excluded from our analysis due to the lack of data relating to the key variables retained. The choice of the period from 1984 to 2017 and the countries of the aforementioned regions is justified by the availability of data. Table 1 includes all the variables studied, their corresponding measurement.

We refer to the WDI database to collect data on the variables related to renewable energy consumption, population growth, foreign direct investment, financial development, gross domestic product, Internet use, and mobile use. The Internet and mobile penetrations are quantified in our studies by individuals using the Internet (% of population) and mobile cellular subscriptions (% of total population), respectively.

We have retained two components of institutional quality, namely the rule of law and the control of corruption, which both are retained from the Worldwide Governance Indicators (WGI) database. Scores ranging from approximately 2.5 to 2.5 are applied to measure these two

**Fig. 1** Conceptual model on the direct and conditional effects of renewable energy consumption on environmental sustainability



**Table 1** Variables definition and measurement

Variable	Definition	Measurement	Source
EG	Ecological gap	The difference between ecological footprint consumption and biocapacity (in global hectares per person)	Global Footprint Network
REN	Renewable energy consumption	Renewable energy consumption (% of total final energy consumption)	WDI
POPG	Population	Population growth (annual %)	WDI
FDI	Foreign direct investment	Foreign direct investment, net inflows (% of GDP)	WDI
FD	Financial development	Financial development index	WDI
GDP	Gross domestic product	GDP per capita growth (annual %)	WDI
GDPS	Gross domestic product square	GDP per capita growth square (annual %)	WDI
LAW	Rule of law	Score ranging from approximately -2.5 to 2.5.	WGI
CORR	Control of corruption	Score ranging from approximately -2.5 to 2.5.	WGI
ICTI	Internet penetration	Individuals using the Internet (% of population)	WDI
ICTM	Mobile penetration	Mobile cellular subscriptions (% of total population)	WDI

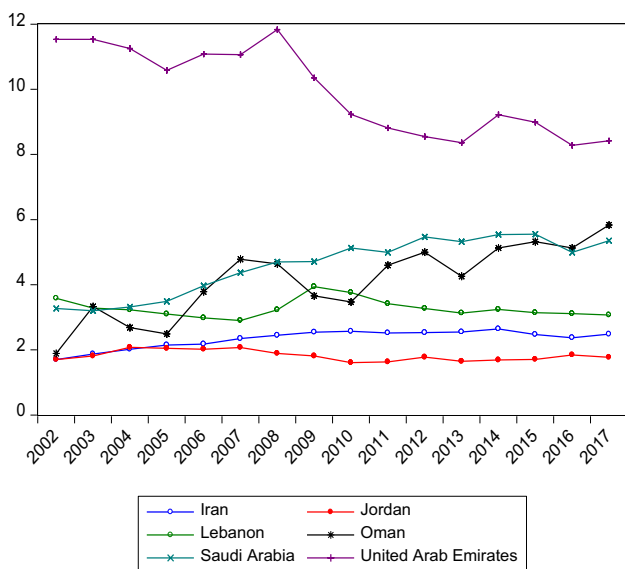


Fig. 2 Ecological gap (in global hectares per person) in ME countries

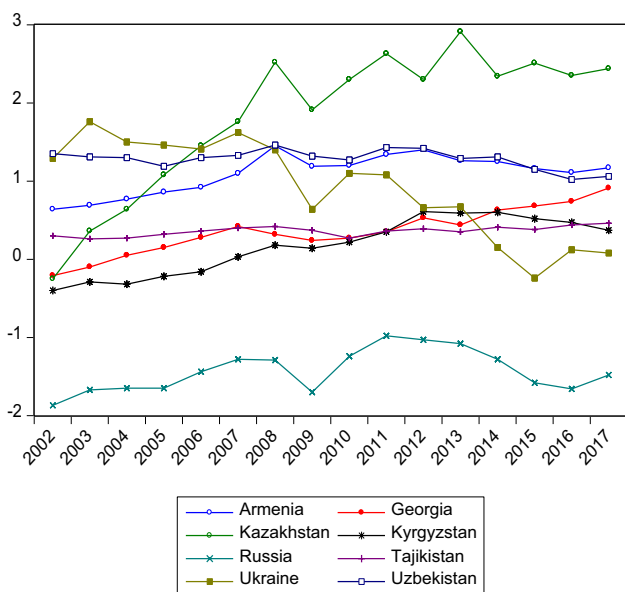


Fig. 3 Ecological gap (in global hectares per person) in CIS countries

variables in accordance with the approach of Kauffman et al. (2008). A set of studies has isolated biocapacity from ecological footprint while examining the factors driving environmental degradation (Khan et al., 2021).

In our study, the dependent variable relating to the ecological gap is calculated by the difference between the ecological footprint and the biocapacity, which are both expressed in global hectares per person and compiled from Global Footprint Network (GFN) database. Figures 2 and 3 retrace the evolution of the ecological gap in selected ME and CIS countries.

The energy consumed in the ME and CIS countries is mainly non-renewable. As shown in Table 2, the renewable energy consumption represents only an average of about 10.5% of the total energy consumed during the period 1984–2017. The predominance of the polluting energy sector is even more worrying given that the economic growth of these countries remains conditioned by the activities related to oil fields and natural resources and therefore, an abuse in environmental exploitation. In return, there have been several institutional reforms and a remarkable boom in the ICT sector in these countries, which could have implications for ecological gap.

### Models

#### Panel quantile regression approach

In our study, we refer to the panel quantile regression with fixed effects in order to examine the conditional distribution of the countries concerning the factors underlying the ecological gap. The panel quantile regression technique was initiated by Koenker and Bassett (1978) in order to overcome the shortcomings of traditional regression methods which lack the relevance and reliability of the estimated coefficients and the fact that they are based on the effects of the means (Binder and Coad, 2011). The reliability and robustness of quantile regression are particularly verified in the case where the data include outliers and heavy distributions. A drawback of this technique relates to its inability to detect the unobserved heterogeneity of individuals. The general form of the conditional quantile of  $y_i$  given  $x_i$  is retraced by Eq. (1) as follows:

$$Q_y(\tau | X_{it}) = X_{it}^T \delta_\tau \tag{1}$$

The panel quantile regression enables to test the conditional heterogeneous covariance effects of renewable energy, financial development, foreign direct investment (FDI), economic growth, population growth, institutional quality, and TICs on ecological gap. The median regression analysis to other quantiles takes the general form given by the following Eq. (2):

$$Q_y(\tau_k | \alpha_i, X_{it}) = \alpha_i + X_{it}' \delta(\tau_k) \tag{2}$$

where  $y$  denotes the conditional quantile,  $x$  represents a  $k$ -dimensional vector of independent variables, and  $\delta(\tau_k)$  is the common slope coefficients. In this last equation,  $\alpha_i$  reflects the individual specific fixed effects parameter. The quantile index is such that  $\tau$  belongs to the interval  $[0, 1]$ . The fixed effects quantile regression estimator as recommended by Koenker (2004) is described as follows:

**Table 2** Summary of descriptive statistics

	Mean	Std.dev	Maximum	Minimum	J.B	Median	Q1	Q3
EG	2.190	2.729	11.830	-1.870	177.310	1.455	0.420	3.120
REN	10.468	16.856	64.580	0.000	189.556	2.827	0.897	7.973
POPG	1.958	2.605	15.177	-0.949	662.647	1.410	0.163	2.759
FDI	4.948	4.160	23.537	-3.175	84.285	3.921	2.031	7.066
FD	0.290	0.139	0.578	0.060	10.836	0.290	0.185	0.389
GDP	2.796	5.113	14.695	-15.151	20.175	2.888	-0.328	5.893
GDPS	33.848	46.589	229.559	0.000	469.737	16.475	4.402	43.286
LAW	-0.473	0.619	0.849	-1.476	17.831	-0.683	-0.954	0.131
CORR	-0.484	0.702	1.280	-1.370	28.127	-0.768	-1.035	0.070
ICTI	31.316	25.684	94.819	0.055	22.014	23.150	8.382	51.300
ICTM	0.873	0.536	2.126	0.002	9.292	0.875	41.200	130.969

$$\min_{(\alpha\delta)} \sum_{k=1}^K \sum_{t=1}^T \sum_{n=1}^N w_k \rho_{\tau_k} \left( y_{it} - \alpha_i - x_i^T \delta(\tau_k) + \lambda \sum_i |\alpha_i| \right) \quad (3)$$

where the index  $i$  describes each country retained (among  $N$  countries),  $T$  denotes the number of observations per countries, and  $K$  is the index for quantiles. From Eq. (2) and by integrating the dependent variable and the list of explanatory variables, the set of models that we estimate is retraced by the following equations (4), (5), (6), (7), and (8).

$$Q_{EG}(\tau_k | \alpha_{1i}, \mu_{1i}, X_{it}) = \alpha_i + \mu_{1i} + \delta_{11\tau} REN_{it} + \delta_{12\tau} POPG_{it} + \delta_{13\tau} FDI_{it} + \delta_{14\tau} FD_{it} + \delta_{15\tau} GDP_{it} + \delta_{16\tau} GDPS_{it} + \varphi_{1\tau it} \quad (4)$$

$$Q_{EG}(\tau_k | \alpha_{2i}, \mu_{2i}, X_{it}) = \alpha_{2i} + \mu_{2i} + \delta_{21\tau} REN_{it} + \delta_{22\tau} POPG_{it} + \delta_{23\tau} FDI_{it} + \delta_{24\tau} FD_{it} + \delta_{25\tau} GDP_{it} + \delta_{26\tau} GDPS_{it} + \delta_{27\tau} LAW + \delta_{28\tau} REN * LAW + \varphi_{2\tau it} \quad (5)$$

$$Q_{EG}(\tau_k | \alpha_{3i}, \mu_{3i}, X_{it}) = \alpha_{3i} + \mu_{3i} + \delta_{31\tau} REN_{it} + \delta_{32\tau} POPG_{it} + \delta_{33\tau} FDI_{it} + \delta_{34\tau} FD_{it} + \delta_{35\tau} GDP_{it} + \delta_{36\tau} GDPS_{it} + \delta_{37\tau} CORR + \delta_{38\tau} REN * CORR + \varphi_{3\tau it} \quad (6)$$

$$Q_{EG}(\tau_k | \alpha_{4i}, \mu_{4i}, X_{it}) = \alpha_{4i} + \mu_{4i} + \delta_{41\tau} REN_{it} + \delta_{42\tau} POPG_{it} + \delta_{43\tau} FDI_{it} + \delta_{44\tau} FD_{it} + \delta_{45\tau} GDP_{it} + \delta_{46\tau} GDPS_{it} + \delta_{47\tau} ICTI + \delta_{48\tau} REN * ICTI + \varphi_{4\tau it} \quad (7)$$

$$Q_{EG}(\tau_k | \alpha_{5i}, \mu_{5i}, X_{it}) = \alpha_{5i} + \mu_{5i} + \delta_{51\tau} REN_{it} + \delta_{52\tau} POPG_{it} + \delta_{53\tau} FDI_{it} + \delta_{54\tau} FD_{it} + \delta_{55\tau} GDP_{it} + \delta_{56\tau} GDPS_{it} + \delta_{57\tau} ICTM + \delta_{58\tau} REN * ICTM + \varphi_{5\tau it} \quad (8)$$

where REN, POPG, FDI, FD, GDP, and GDPS represent renewable energy consumption, population growth, foreign direct investment inflows, gross domestic product, and gross domestic product square, respectively. We retained two representative variables of institutional quality, which are the rule of law (LAW) and the control of corruption (CORR). With regard to information and communication technologies, we based on the Internet use (ICTI) and mobile use (ICTM). The interaction terms REN \* LAW and REN \* CORR added in Eqs. (5) and (6) denote the moderating effects of institutional quality in the relationship between renewable energy consumption and the ecological gap, respectively. Similarly, in order to examine the conditional effects of renewable energy consumption on the ecological gap through ICTs, we have integrated the interactive terms REN \* ICTI in Eq. (7) and REN \* ICTM in Eq. (8). The role played by green ICT is measured by the interaction term between ICT and renewable energy. In these last equations, the ecological gap (EG) as dependant variable is measured by the difference between ecological footprint and biocapacity ( $EG = EFP - BC$ ).

### Kao cointegration test

The cointegration test is conducted once the integrating properties of the series with respect to the different covariates of the model were checked. In this study, we based on the Kao cointegration test in order to ensure the presence of a non-spurious long-term relationship between the variable relating to ecological gap, the core variables, and the other covariates. This test is usually used in particular in the case where cointegration vectors are homogeneous between individuals (Barbieri, 2008). The specificity of the Kao test is that it takes into account on the first-stage regressors, cross-section specific intercepts, and homogeneous coefficients. Kao (1999) describes the bivariate configuration starting with the following Eqs. (9), (10), and (11).



$$y_{it} = \gamma_i + \beta x_{it} + \omega_{it} \tag{9}$$

For

$$y_{it} = y_{it-1} + \epsilon_{it} \tag{10}$$

$$x_{it} = x_{it-1} + \epsilon_{it} \tag{11}$$

where  $i$  and  $t$  are the indices relating to individuals and to the temporal axis such that  $i = 1, \dots, N$  and  $t = 1, \dots, T$ . To carry out the first stage regression,  $\gamma_i$  should be heterogeneous and  $\beta_i$  homogeneous between the cross-sectional data and assigning zero values to the trend coefficients. The next step is to carry out either the pooled auxiliary regression formulated as follows:

$$\epsilon_{it} = \rho \epsilon_{it-1} + \vartheta_{it} \tag{12}$$

or the pooled specification of its augmented version which is described as follows:

$$\epsilon_{it} = \tilde{\rho} \epsilon_{it-1} + \sum_{j=1}^P \partial_j \Delta \epsilon_{it-j} + \vartheta_{it} \tag{13}$$

By postulating the absence of cointegration under the null hypothesis, and for  $\rho > 0$  with augmented version Kao indicated the following statistics:

$$DF_{\rho} = \frac{T\sqrt{N}(\hat{\rho} - 1) + 3\sqrt{N}}{\sqrt{10.2}} \tag{14}$$

$$DF_t = \sqrt{1.25}t_{\rho} + \sqrt{1.875}N \tag{15}$$

$$DF_{\rho} = \frac{\sqrt{NT}(\hat{\rho} - 1) + 3\sqrt{N}\hat{\sigma}_{\vartheta}^2/\hat{\sigma}_{0\vartheta}^2}{\sqrt{3 + 36\hat{\sigma}_{\vartheta}^4/(5\hat{\sigma}_{0\vartheta}^4)}} \tag{16}$$

$$DF_t^* = \frac{t_{\rho} + \sqrt{6N} \hat{\sigma}_{\vartheta} / (2\hat{\sigma}_{0\vartheta})}{\sqrt{\hat{\sigma}_{0\vartheta}^2 / (2\hat{\sigma}_{\vartheta}^2) + 3\hat{\sigma}_{\vartheta}^2 / (10\hat{\sigma}_{0\vartheta}^2)}} \tag{17}$$

$$ADF = \frac{t_{\rho} + \sqrt{6N} \hat{\sigma}_{\vartheta} / (2\hat{\sigma}_{0\vartheta})}{\sqrt{\hat{\sigma}_{0\vartheta}^2 / (2\hat{\sigma}_{\vartheta}^2) + 3\hat{\sigma}_{\vartheta}^2 / (10\hat{\sigma}_{0\vartheta}^2)}} \tag{18}$$

Converge to  $N(0, 1)$  asymptotically. In these last equations,  $\hat{\sigma}_{\vartheta}^2 = \hat{\sigma}_{\epsilon}^2 - \hat{\sigma}_{\epsilon\epsilon}^2 \hat{\sigma}_{\epsilon}^{-2}$  represents estimated variance and  $\hat{\sigma}_{0\vartheta}^2 = \hat{\sigma}_{0\epsilon}^2 - \hat{\sigma}_{0\epsilon\epsilon}^2 \hat{\sigma}_{0\epsilon}^{-2}$  indicates estimated long run variance.

### Slope and symmetric quantiles tests

To check if the slopes between quantiles are the same, as for heteroscedasticity, we based on the approach of Koenker and Bassett (1982). The null hypothesis, proposed by these authors, takes the following form:

$$H_0 : \delta_1(\tau_1) = \delta_1(\tau_2) = \dots = \delta_1(\tau_k) \tag{19}$$

This test assumes the existence of  $(p - 1)(k - 1)$  restrictions on the coefficients. By referring to this null, Wald statistics can be determined and which is distributed as  $\chi_{(p-1)(k-1)}^2$ .

The symmetric quantile test is associated with the estimates provided by panel quantile regression and introduced by Newey and Powell (1987). In case where the distribution of  $Y$  for the given  $X$  is symmetric, this test supposes that:

$$\frac{\delta(\tau) + \delta(\tau - 1)}{2} = \delta\left(\frac{1}{2}\right) \tag{20}$$

Along the quantile process, the test is based on the Wald test to evaluate this restriction. By assuming that the estimated coefficients ordered by  $\tau_k$  exist in a  $K$  sets, the mean value  $\tau_{(k+1)/2}$  is equal to 0.5, and the remaining  $\tau$  are symmetric equal to 0.5. By considering  $\tau_j = 1 - \tau_{k-j+1}$ , for  $j = 1, \dots, (K - 1)/2$ , the null hypothesis can be formulated as follows:

$$H_0 : \frac{\delta(\tau_j) + \delta(\tau_{k-j-1})}{2} = \delta\left(\frac{1}{2}\right) \text{ for } j = 1, \dots, \frac{(k-1)}{2} \tag{21}$$

Under the null hypothesis of symmetry, the Wald test is equal to 0. The Wald statistics are distributed as  $\chi_{p(k-1)/2}^2$  with  $p(K - 1)/2$  restrictions. We expect that by referring to the slope and symmetric quantiles tests, we obtain a more complete explanation of the driving forces of ecological gap.

### Results and discussion

The study focuses on the direct ecological effects of renewable energy as well as its ecological effects moderated by the institutional quality and the TICs. These effects, along with those of other covariates, are examined at different scales of the ecological gap. Before analysing the effects of the different variables selected, a preliminary standard study is necessary. We start with the study of cross-sectional dependence to ensure the absence of common

unobserved factors, which could lead to non-robust results (Phillips & Sul, 2003). We use the LM and CD tests recommended by Breusch and Pagan (1980) and Pesaran (2004). We support the analysis of the cross-sectional dependence also through the tests of Pesaran (2004) scaled LM and bias-corrected scale LM. As shown in Table 3, the results of these tests all reveal that the null hypothesis is rejected, and therefore, cross-sectional dependence occurs for all the variables selected.

Since the absence of stationarity generates biased and spurious results, unreliable forecasts, and the inability to select the most appropriate model, we proceed with unit root tests. We apply the Levin Lin Chu (LLC) and the Im, Pesaran, and Shin (IPS) stationary tests. While the LLC test homogeneously determines autoregressive parameters, the IPS test refers to the individual stationary processes by tolerating the heterogeneity of these parameters (Intisar et al., 2020). The two tests indicate that all the variables are stationary in first difference. According to LLC test, with the exception of the Internet use and the mobile use, which are integrated of order 1, all the other variables are integrated of order 0. The same variables representative of the ICTs are also integrated of order 1 according to IPS test to which are added the variables relating to the ecological gap and the renewable energy consumption (Table 4).

After confirming the stationarity of the variables, we examine the cointegration based on the Kao test. As shown in Table 5, cointegration is strongly supported for all models retained (1, 2, 3, 4, 5) with moderation and without moderation. There is, therefore, a long-term cointegration relationship between the variables.

To study the ecological effects of the various explanatory variables, we use three quantiles  $Q1 = 0.1$ ,  $Q2 = 0.5$ , and  $Q3 = 0.9$  which reflect three possible configurations which are, low ecological gap, medium ecological gap, and high ecological gap, respectively.

The results of the quantile regression panel revealed that renewable energy consumption reduces the ecological gap, but their effects are not always significant. As shown in Tables 6 and 7, the beneficial ecological effects of renewable energy consumption are verified in 4 out of 5 models with low ecological gap, 3 out of 5 models with medium ecological gap, and 2 out of 5 models with high ecological gaps. So, hypothesis H.1 is partially confirmed. Our results contradict those of Usman et al. (2020) concerning the effects of renewable energy and financial development. Indeed, according to these authors, financial development and non-renewable energy utilization caused deterioration in ecological footprint in 20 highest emitting economies. Our results partially confirm those of Sharif et al. (2020) who reported that renewable energy reduces the ecological footprint on each quantile. As shown in Table 6, the regulatory framework in the selected ME and

**Table 3** Panel cross sectional dependence results

Test	EG	REN	POPG	FDI	FD	GDP	GDPS	LAW	CORR	ICTI	ICTM	
Breusch-Pagan LM	Statistic	540.222	428.597	468.113	271.305	471.537	273.350	194.582	233.417	238.646	1340.858	1221.852
	P-value	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
Pesaran scaled LM	Statistic	33.298	25.024	27.953	13.365	28.207	13.516	7.678	10.556	10.944	92.645	83.824
	P-value	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
Biais-corrected scaled LM	Statistic	32.831	24.557	27.486	12.898	27.740	13.050	7.211	10.089	10.477	92.178	83.357
	P-value	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
Pesaran CD	Statistic	5.534	1.740	9.921	10.431	11.473	8.3347	6.475	5.409	3.609	36.600	34.895
	P-value	0.000	0.081	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000

**Table 4** Unit root test results

	LLC test		Result	IPS test		Result
	Level	First difference		Level	First difference	
EG	-1.528*	-9.410***	I0	1.249	-6.120***	I1
REN	-1.717**	-9.691***	I0	0.206	-7.147***	I1
POP	-20.678***	-10.535***	I0	-8.023***	-7.087***	I0
FDI	-4.364***	-11.030***	I0	-3.448***	-8.294***	I0
FD	-3.542***	-7.825***	I0	-2.952***	-5.687***	I0
GDP	-6.229***	-10.454***	I0	-3.019***	-7.128***	I0
GDPS	-7.857***	-13.227***	I0	-5.330***	-11.546***	I0
LAW	-2.964***	-10.171***	I0	-1.696**	-8.440***	I0
CORR	-5.454***	-8.823***	I0	-4.009***	-7.137***	I0
ICTI	-0.831	-4.862***	I1	0.542	-3.251***	I1
ICTM	-0.240	-6.298***	I1	2.006	-3.734***	I1

\*\*\*, \*\*, and \* denote that coefficient is significant at the level of 1%, 5%, and 10%, respectively

**Table 5** KAO cointegration test

	ADF		HAC variance	Residual variance
	t-Statistic	P-value		
Model 1: f (REN; POPG; FD; FDI; GDP; GDPS)	-2.361	0.009	0.100	0.107
Model 2: f (REN; POPG; FD; FDI; GDP; GDPS; LAW; RENLAW)	-2.566	0.005	0.094	0.107
Model 3: f (REN; POPG; FD; FDI; GDP; GDPS; CORR; RENCORR)	-2.288	0.011	0.098	0.107
Model 4: f (REN; POPG; FD; FDI; GDP; GDPS; ICTI; RENICTI)	-2.8881	0.001	0.083	0.106
Model 5: f (REN; POPG; FD; FDI; GDP; GDPS; ICTM; RENICTM)	-3.100	0.001	0.088	0.107

**Table 6** Conditional effects of institutional quality according to ecological gap level

Variables	Low ecological gap Q1 = 0.1			Medium ecological gap Q2 = 0.5			High ecological gap Q3 = 0.9		
	Model 1	Model 2	Model 3	Model 1	Model 2	Model 3	Model 1	Model 2	Model 3
REN	-0.039***	-0.085	-0.052***	-0.014**	-0.046***	-0.091***	-0.009	-0.110***	-0.125***
POPG	0.617***	0.452***	0.480***	0.507***	0.542***	0.457***	0.523***	0.366***	0.285***
FDI	0.007	0.007	0.011	-0.003	-0.007	0.012	-0.012	-0.036	0.083***
FD	-4.365***	-6.465***	-6.435***	6.359	0.002	-4.588***	13.343**	2.328	0.186
GDP	0.004	0.053	0.030	-0.007	0.008	0.007	0.015	0.065***	0.026
GDPS	0.005**	-0.003	-0.001	0.006***	0.004	0.001	0.003	0.001	-0.001
LAW		1.244**			1.339***			3.431***	
REN * LAW		-0.031			-0.020			-0.077***	
CORR			1.244***			2.407***			3.195***
REN * CORR			-0.003			-0.052***			-0.088***
Constant	0.552	2.684***	2.640***	-0.564	1.909	4.129***	-0.917	4.784***	4.650***

\*\*\*, \*\*, and \* denote that coefficient is significant at the level of 1%, 5%, and 10%, respectively

CIS countries worsens the environmental degradation to the extent that the effects of the rule of law on the ecological gap are significantly positive across all quantiles. The regulatory framework in the ME and CIS countries seems to reinforce the excessive exploitation of the environment since these countries are natural resources-dependent

economies. Our findings also report that the control of corruption does not also mitigate the ecological gap across all quantiles. The institutions established in the ME and CIS countries are oriented towards economic rents and not the management and control of the ecological costs generated by these rents. The role of renewable energy consumption

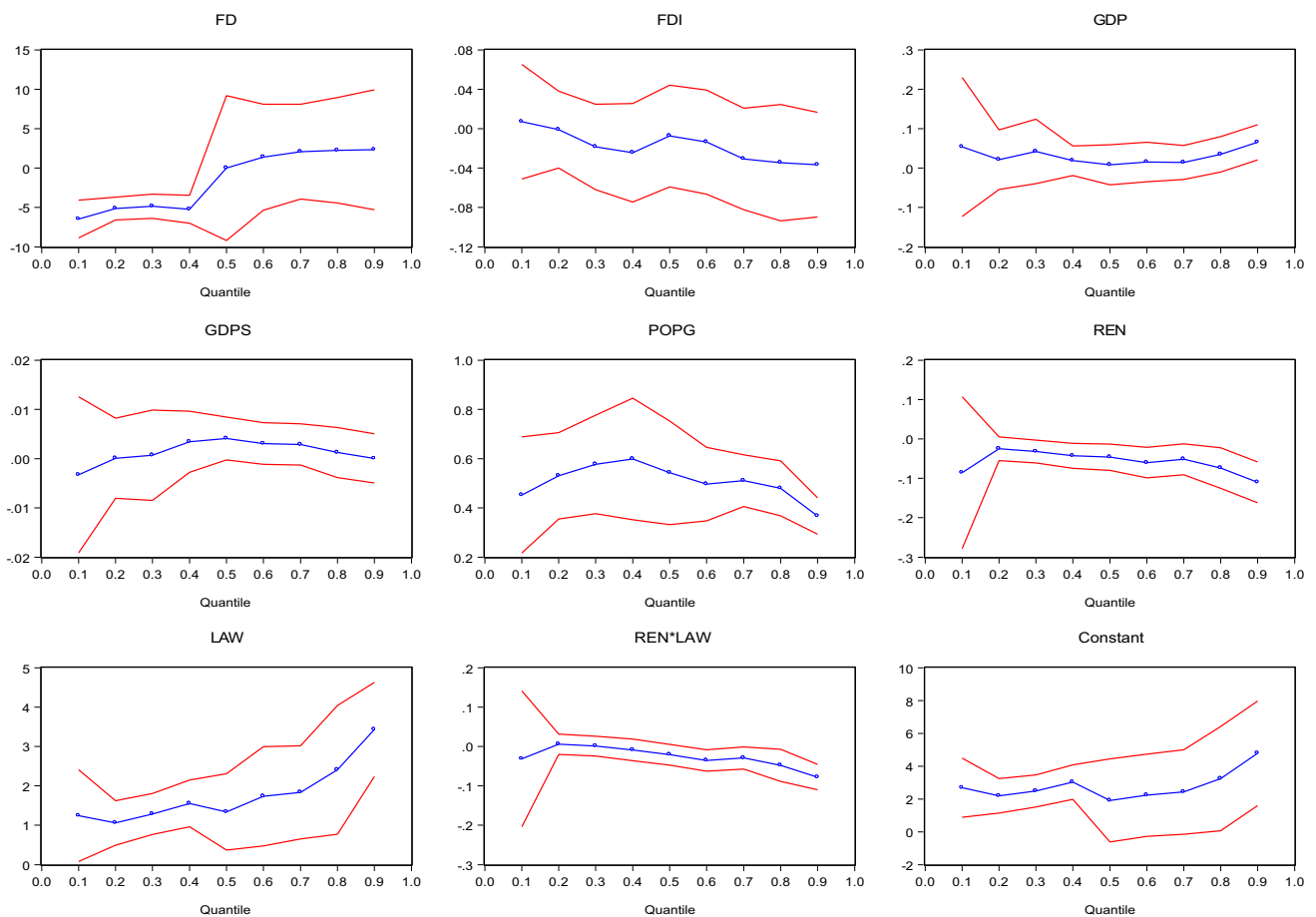
**Table 7** Conditional effects of ICTs according to ecological gap level

Variables	Low ecological gap Q1 = 0.1		Medium ecological gap Q2 = 0.5		High ecological gap Q3 = 0.9	
	Model 4	Model 5	Model 4	Model 5	Model 4	Model 5
REN	-0.030***	-0.024***	-0.008	-0.007	-0.012	0.013
POPG	0.579***	0.640***	0.496***	0.510***	0.422***	0.533***
FDI	0.040	0.005	0.002	-0.003	0.016	-0.007
FD	-4.436***	-4.003***	4.966*	5.132**	3.225	9.015**
GDP	0.008	0.022	-0.004	-0.001	0.026	0.051
GDPS	0.005*	0.006**	0.005***	0.005***	-0.001	0.004
ICTI	0.008		0.013**		0.061***	
REN * ICTI	-0.001		-0.001***		-0.002***	
ICTM		0.250		0.526**		2.116***
REN * ICTM		-0.009		-0.020***		-0.071***
Constant	0.398	0.087	-0.464	-0.562	0.679	-1.231

\*\*\*, \*\*, and \* denote that coefficient is significant at the level of 1%, 5%, and 10%, respectively

played in reducing the ecological gap is conditioned by the rule of law only under high quantile. Corruption control is important so that the effects of renewable energy consumption on the ecological gap are beneficial in the case of medium and high quantiles. These findings reflect that

hypothesis H.3 is partially confirmed since the effects of renewable energy consumption on environmental sustainability are favourably moderated by the rule of law only in the case of high ecological gap and by the control of corruption in the case of medium and high ecological gap.



**Fig. 4** Panel quantile plots at 95% confidence (rule of law)

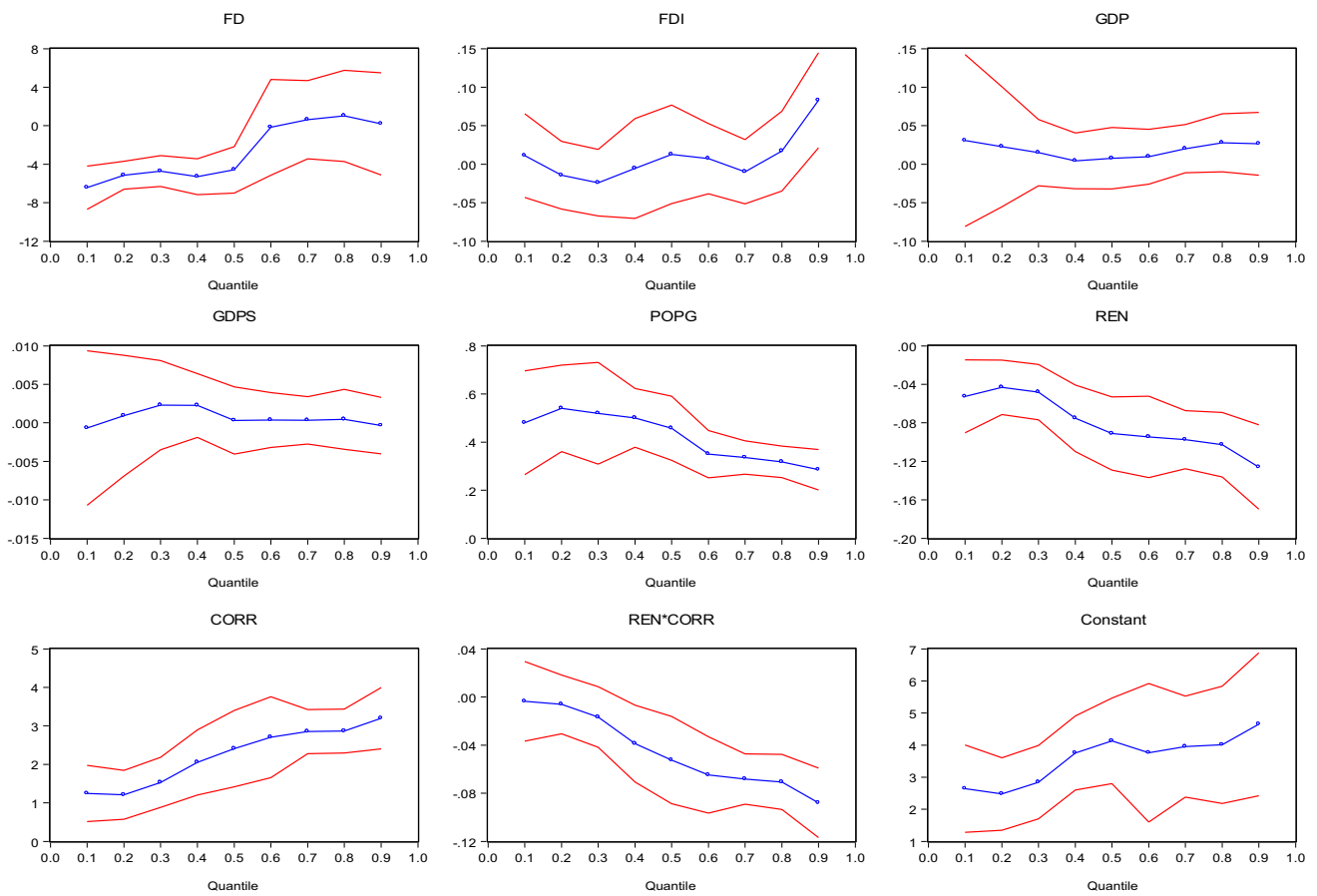


Fig. 5 Panel quantile plots at 95% confidence (control of corruption)

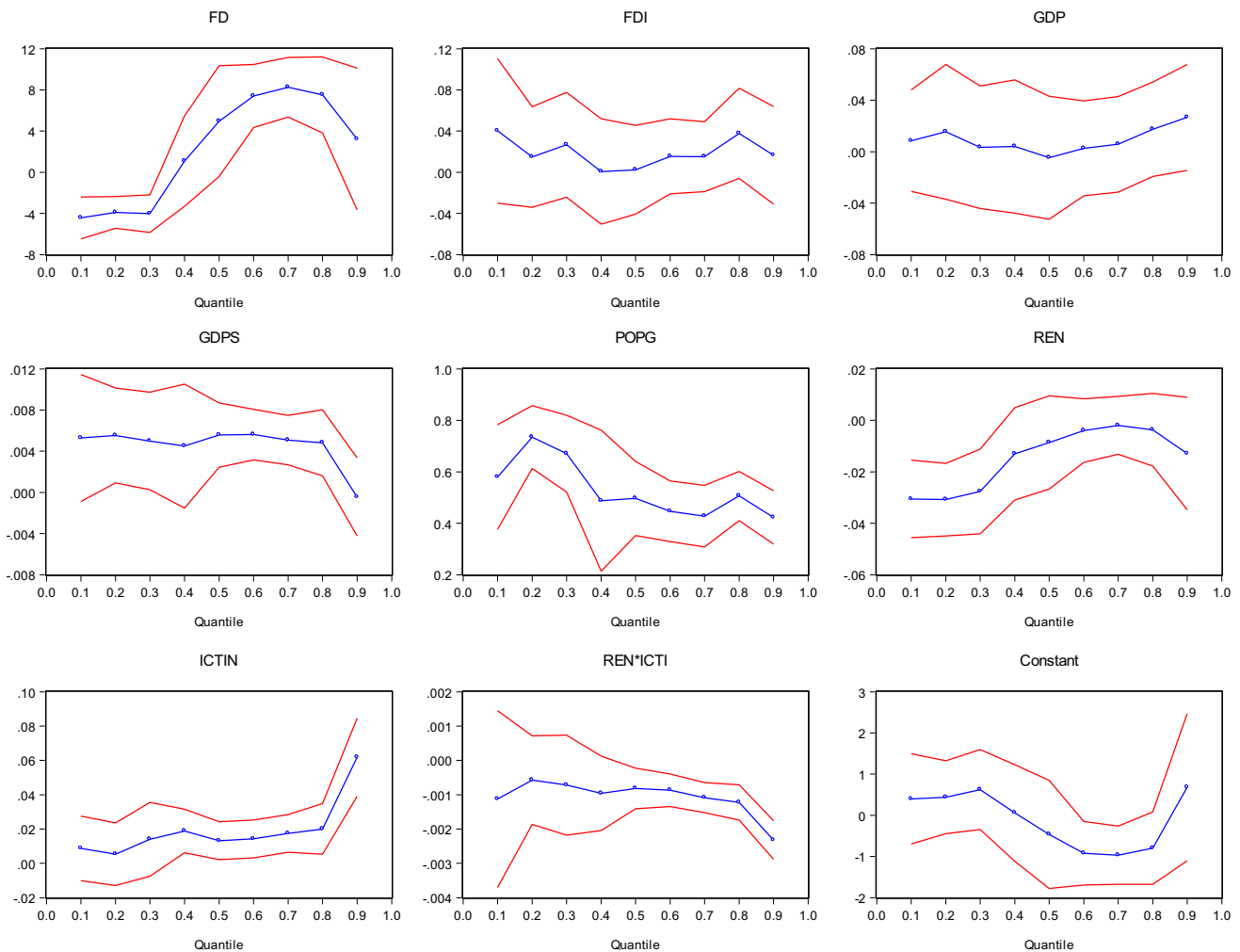
Table 8 Slope and symmetric quantiles tests

		Slope test		Symmetric quantile test	
		Chi-sq. statistic	P-value	Chi-sq. statistic	P-value
Model 1	Q = 0.1	154.338	0.000	38.731	0.000
	Q = 0.5	131.178	0.000	36.464	0.000
	Q = 0.9	138.920	0.000	38.731	0.000
Model 2	Q = 0.1	125.157	0.000	25.917	0.101
	Q = 0.5	91.876	0.000	6.740	0.664
	Q = 0.9	217.607	0.000	25.917	0.101
Model 3	Q = 0.1	167.064	0.000	33.285	0.015
	Q = 0.5	107.727	0.000	16.537	0.056
	Q = 0.9	154.399	0.000	33.285	0.015
Model 4	Q = 0.1	191.069	0.000	37.114	0.005
	Q = 0.5	146.437	0.000	17.377	0.043
	Q = 0.9	243.728	0.000	37.114	0.005
Model 5	Q = 0.1	183.469	0.000	55.609	0.000
	Q = 0.5	139.776	0.000	39.457	0.000
	Q = 0.9	169.117	0.000	55.609	0.000

The quantiles process traced by Figs. 4 and 5 (at 95% confidence) consolidates our results of estimates concerning the effects of the rule of law and the control of corruption as well as their moderating effects in the relationship between renewable energy consumption and the ecological gap.

From Table 7, ICTs whether measured by Internet use and mobile use are harmful to the environment at medium and low quantiles. Their effects are positive and significant on environmental degradation for countries with medium and high ecological gaps. Our findings contradict those of Halder and Sethi (2022) given that the ecological effects of ICTs are disastrous except for countries with weak ecological gaps. Although ICTs have negative effects on environmental sustainability, their ecological effects are beneficial when they interact with the consumption of renewable energy in countries with medium and high ecological gaps. The interaction terms between the renewable energy consumption and each of the variables relating to Internet use and mobile use are negative at medium and high quantiles. Based on these results, hypothesis H.2 is partially confirmed since the effects of the renewable energy consumption on the





**Fig. 6** Panel quantile plots at 95% confidence (Internet users)

environmental sustainability are favourably moderated by the institutional quality only in the case of medium and high ecological gap. The use of ICTs must be oriented towards clean energy so that it can mitigate the ecological footprint, and preserve biocapacity and, therefore reduce environmental degradation. It is important to channel these ICTs, to substitute their intensive use in polluting activities with green ICTs, especially for countries characterized by high ecological gaps. The Internet and mobile use to preserve the environment are necessary but insufficient as long as they constitute a joint product of the industrial sector.

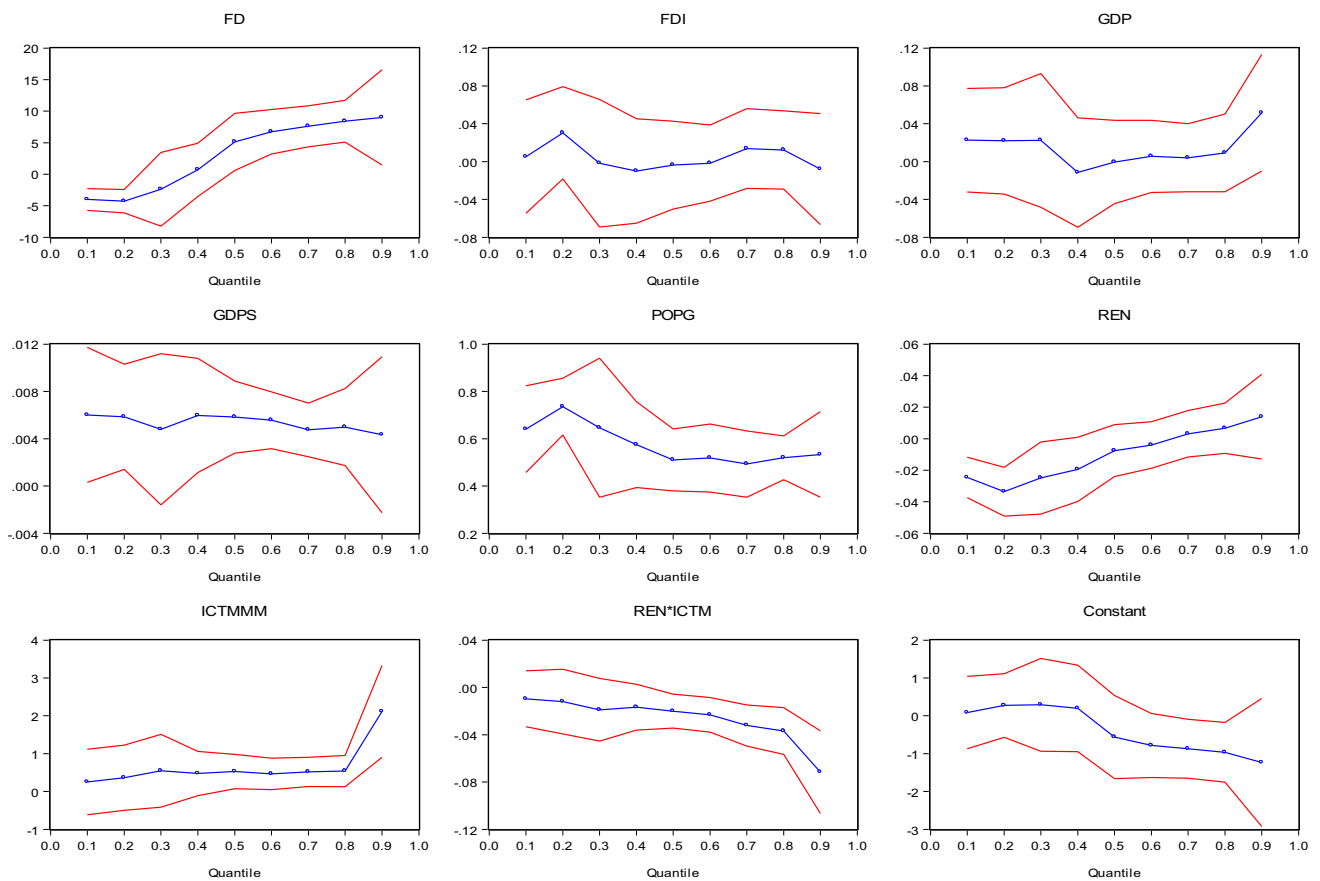
With regard to other covariates, it emerges that FDI in the case of the ME and CIS countries are mobilized by the search for natural resource rents and therefore, do not generate any positive effect on the environment quality.

Our results support for all quantiles the findings of Ahmed et al. (2020) who highlighted the perverse effect

of urbanization on ecological footprint in the case of G7. However, in the case of our research, the negative effects of urbanization measured by population growth go beyond to concern the ecological gap.

As indicated in Tables 7 and 8, environmental degradation is reduced under the effect of financial development in the case of countries with low ecological gaps for all models. Our findings reject those of Danish et al. (2020) and invalidate the EKC in the case of the ME and CIS countries by relying on ecological gap as indicator of environmental degradation. The process quantiles (at 95% confidence) illustrated by Figs. 6 and 7 also support our findings regarding the direct and moderating effects of ICTs on the ecological gap.

Table 8 shows that for all models, chi-sq. statistic values are statistically significant at the 1% threshold, which reflect that the null hypothesis of slope equality across quantiles is rejected. This result indicates that the relationship between the



**Fig. 7** Panel quantile plots at 95% confidence (mobile subscriptions)

set of independent variables and the ecological gap varies across quantiles.

In addition, the chi-sq. statistic relating to the symmetric quantiles test is significant for all the models except for model 2. This translates that the null hypothesis postulating that the distribution is symmetric is rejected for models 1, 3, 4, and 5. For these last models, there is an asymmetric relationship between the quantiles and thus, the presence of heterogeneous effects of the explanatory variables on the ecological gap.

### Conclusion and policy implications

The factors enabling beneficial ecological effects of the renewable energy sector are currently of great importance. This study provides two essential tools, making it possible to condition the effects of renewable energy use on the ecological gap in the case of economies rich in natural resources, which are institutional quality and ICTs. Our findings highlight the role played by institutions through a solid regulatory framework and the control of corruption to channel the renewable energy consumption and therefore, reduce the ecological footprint and preserve biocapacity. The rule of

law reinforces the positive effects of renewable energy on the environment for countries with a high ecological gap. The control of corruption in the renewable energy sector is also beneficial in mitigating environmental degradation for countries with medium and high ecological gaps. Polluting energy demand provided by ICT is observed at medium and high ecological gap. Indeed, environmental degradation generated by ICTs is recorded in countries with medium and high ecological gaps. These harmful effects of ICTs on the environment are reversed when they interact with the renewable energy use in countries with medium and high ecological gaps. Thus, Internet use and mobile use are assimilated both, as part of the problem through more polluting energy demand, as well as part of the solution by providing more energy efficiency.

Based on these results, it is interesting for the ME and CIS countries, in particular with high ecological gaps, to implement an adequate regulatory framework organizing and managing the renewable energy sector. The implementation of nature restoration laws and legislation for environmental risk mitigation are currently essential for these countries. The ME and CIS countries with medium and high ecological gaps are required to control any attempt

of corruption in the green energy field through the fight against the spread of the phenomenon of bribery especially within public administrations, lackluster legislation towards the environment, and favouritism. Moreover, these countries must stop being guided only by rent-seeking to the detriment of the environment. Moreover, ICTs should be directed towards the renewable energy sector so that energy efficiency can be achieved which, in turn helps to minimize the ecological gap. To reverse the negative effects of Internet use and mobile use recorded at medium and high ecological gap, these ICTs must be used extensively in renewable energy sectors. Our findings discouraged the harmful effects of ICTs on the sustainability of the environment, particularly in the event of a high ecological gap. However, these results may not yet be relevant because this study was not based on the calculation of an index or a measure of green ICT and did not distinguish it from other types of ICT. Therefore, it is interesting for subsequent studies to conduct a more in-depth analysis of the ecological repercussions of ICTs by focusing more particularly on the environmental implications of green ICTs.

**Acknowledgements** The authors gratefully acknowledge Qassim University, represented by the Deanship of Scientific Research, for the financial support for this research under the number 10327-cbe-2020-1-3-I during the academic year 1442 AH/2020 AD.

**Author contribution** Conceptualization: Tarek Bel Hadj; methodology: Tarek Bel Hadj, Adel Ghodbane; formal analysis and investigation: Tarek Bel Hadj, Ezzedine Ben Mohamed; writing — original draft preparation: Abdullah Abdulmohsen Alfalih; writing — review and editing: Tarek Bel Hadj, Adel Ghodbane; funding acquisition: Tarek Bel Hadj.

**Funding** This research was funded by the Qassim University in Saudi Arabia, grant number 10327-cbe-2020-1-3-I. The APC was funded by the Qassim University.

**Data availability** The data are available upon demand by request to the corresponding author.

## 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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