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Research article

Does information and communication technology impede environmental degradation? fresh insights from non-parametric approaches

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A B S T R A C T

Although ICT has played a critical role in the socio-economic growth of human cultures, it has also brought with it significant environmental risks. Nevertheless, scholars remain divided on this topic; some believe that ICT has had a positive influence on the quality of the environment, while others believe that ICT has created major environmental issues. Hence, this research is another effort to assess the effects of ICT on CO_2 emissions in the top 10 ICT nations (Denmark, Japan, Luxemburg, South Korea, Netherlands, Iceland, Norway, Sweden, Switzerland, and the United Kingdom) using a dataset from the period between 1986Q1 and 2019Q4. All prior studies have established symmetric association between ICT and CO_2. As a result, we applied the novel non-parametric approaches (quantile-on-quantile regression and Granger causality in quantile) to assess this association. The findings from the QQR uncovered that in the majority of the quantiles, for Denmark, Japan, Luxemburg, Netherland, Norway, Sweden, United Kingdom and Switzerland, the effect of ICT on CO_2 emissions is negative, while in the majority of the quantiles, the effect of ICT on CO_2 emissions is positive for the Netherlands, South Korea, and Iceland. Furthermore, we applied the novel Granger causality in the quantiles approach and the outcomes provided evidence of bidirectional causality between CO_2 emissions and ICT in all the selected nations. The study proposes that sustainable ICT should be used to improve carbon reduction and energy savings potential by optimizing other industries, including managing and monitoring energy usage.

1. Introduction

Climate change and global warming have been among the most contentious problems among governments, scientific institutions and policymakers since the early 21st century (Awosusi et al., 2022; Chatti et al., 2019; Miao et al., 2022; Obumneke et al., 2022). Environmental degradation remains an impediment to the model of sustainable economic growth because it brings a plethora of environmental challenges, including energy dependence, deforestation, climate change, air pollution and pure water scarcity, all of which have been viewed as major threats since the 1960s (Akadiri et al., 2021; Fareed et al., 2021; Shan

et al., 2021; Adebayo et al., 2022; AbdulKareem et al., 2022). Due to harsh weather, droughts, rising sea levels and other health issues, growing carbon emissions (CO_2) and other greenhouse gas (GHG) emissions represent huge challenges to the future of humanity (Abdouli and Hammami, 2017; Adeshola et al., 2021; Adebayo and Kirikkaleli, 2021). As a result, scholars and environmentalists are attempting to investigate factors that, on the one hand, contribute to the reduction of CO_2 while still fostering global economic expansion. Information and Communication Technology (ICT) is one such factor that has completely revolutionized human civilization. Moreover, ICT has made a significant contribution to both emerging and developed nations' growth (Chatti,

2021; Palvia et al., 2018; Güngör et al., 2021; Kirikkaleli and Adebayo, 2021).

Although the importance of ICT in fostering economic expansion cannot be exaggerated given its extensive use in advanced nations, its role in harming the environment is contentious (Danish et al., 2020; Palvia et al., 2018). ICT footprints are becoming more potent, and as a result, the consumption of energy due to ICT use has increased at a rapid rate of 7% per year over the previous few decades (Chaabouni and Saidi, 2017). By 2012, the global energy usage due to ICT-related products had increased to 4.7%, an increase of 3.9% compared to 2007 (Chatti, 2021). Resultantly, by 2012, the overall contribution of the ICT industry to global CO_2 emissions had reached 2% (*Greenpeace International Greenpeace*, 2014). The ICT industry's share of CO_2 emissions is rising because the production of ICT-related components pollutes the ecosystem, while on the other hand, increased usage of the internet, computers, mobile phones, and other devices has augmented the demand for energy, which is a major contributor to the degradation of the environment (Ahmed and Le, 2021).

The majority of research on the influence of ICTs on environmental issues has investigated the impact from the lens of energy usage. One line of research found that ICT has a positive influence on environmental contamination due to the increased consumption of energy as a result of the development of a wide range of ICT-linked products and their widespread use (Asongu, 2018; Avom et al., 2020; Lee and Brahmasrene, 2014; Raheem et al., 2020). Other studies have examined the positive influence of ICT on environmental quality as a result of the greater usage of ICTs, which improves the efficiency of the energy sector and thus reduces CO_2 and other GHG emissions (Chatti, 2021; Irawan, 2014; Liu et al., 2021; Purewal and Haini, 2021; Usman et al., 2021; Wang and Xu, 2021). As a result, we can infer that ICT products have an impact on CO_2 emissions; nevertheless, it is not yet known whether the path of this effect is positive or negative. Thus, using the top 10 ICT nations, we assessed the effect of ICT on CO_2 emissions. In all of the nations studied, mobile usage is increasing at a faster rate (See Figure 1). These nations (South Korea, Netherlands, Iceland, Norway, United Kingdom, Denmark, Sweden, Japan, Switzerland and Luxemburg) are top ICT users and are developed nations. The goal of picking this nation is to guide these nations' pollution reduction initiatives. These nations make a major contribution to global economic output. As a result, it is worthwhile to explore the impact of ICT on CO_2 emissions in these nations.

Furthermore, the debate of whether ICT growth is a factor affecting CO_2 emissions is supported in this study, due to the growing global integration in developed economies, where communication technologies are expediting the distribution of information.

In addition, in most past studies, the scholars have utilized Panel data that has the issue of aggregation bias and gives prejudiced outcomes. To circumvent this issue, we have utilized the time series data, which offer results of each nation individually. The current paper is driven by the debate surrounding the impact of ICT on CO_2 emissions, with the aim of assessing the effect of ICT on CO_2 emissions in the top 10 ICT countries. The primary intention of the research is to contribute to the ongoing body of studies in three areas:

a. This research assesses the ICT-CO_2 emissions nexus by applying the quantile-on-quantile (QQ) approach proposed by Sim and Zhou (2015). The distinctiveness of the QQR approach lies in its capacity to amalgamate the fundamentals of non-parametric estimation and analysis of quantile regression. In addition, the QQR method shows the effectiveness of recognizing the due interrelationship between the variables across different quantiles of the distribution.

b. Moreover, the results gathered from the current paper will offer an inclusive illustration of the critical ICT–CO_2 emissions interrelationship that traditional approaches are unable to detect. This will aid in capturing the nature of the asymmetric interrelationship between the quantiles of ICT and CO_2, which traditional linear estimation methods fail to do, while also providing a broader clarification of the interconnectedness and associations between ICT and CO_2. To the best of the authors' understanding, this is the first paper to apply the QQR approach to assess the interconnection between ICT and CO_2 emissions. Thus, the current paper fills the gap in the literature.

c. Finally, we utilize the innovative Granger causality in quantiles developed by Troster et al. (2018), which explores the causal interrelationship in all quantiles. We can distinguish between the causation impacting the tails of the distribution and the median by using this technique. In addition, the Troster et al. (2018) methodology is reliable over a variety of quantiles, and it emphasizes the non-linear condition in a QR model.

The remaining sections are organized as follows: Section 2 presents a synopsis of past studies, which is followed by the data and methods in
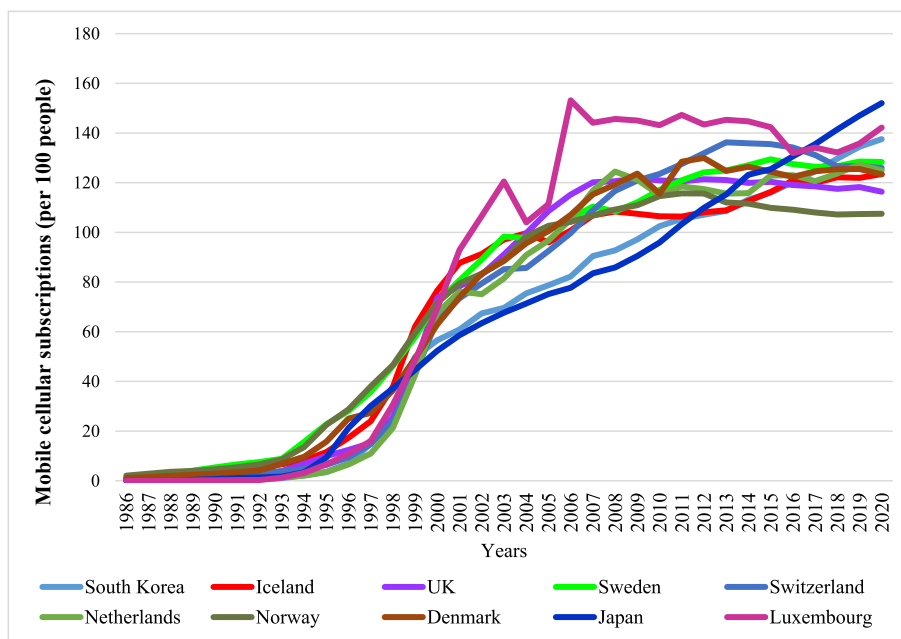

Figure 1. Mobile cellular subscriptions trend.

Section 3. The findings and discussion are presented in Section 4 and Section 5 concludes the research.

2. Literature review

ICT is widely mentioned as a critical component of socio-economic growth. ICT can play a critical role in terms of health, education, culture, income disparity, poverty alleviation, employment, living standards, trade, consumption of energy, and economic expansion (Faisal et al., 2020). ICT is also projected to have a positive influence on governmental responsiveness and openness, healthcare and education options, cultural inventiveness, and the social integration of nations with diverse cultural origins. Government agencies, investors, foreign and international agencies, public and private enterprises, non-governmental organizations, and political groups are all involved in the economic and social growth of any nation. Modernization theory (Grossman and Krueger, 1991), social development theory (Hakkio and Rush, 1991), and economic development theory (Hakkio and Rush, 1991) are some of the concepts that explain the development process (Haseeb et al., 2019). Social traditions, health, social contacts, and the growth of fashion, education and trends are all examples of social development (Houghton, 2010). Economic development, on the other hand, includes jobs creation, improved standards of living, and significant economic expansion (Güngör et al., 2021). Although both theories suggest that ICT has played a very important role in economic and social growth, they differ in terms of the nature of such contributions.

Over the years, significant scholars established that ICT plays a crucial role in abating deterioration of the environment. For example, the research of Irawan (2014) found that ICT abates the deterioration of the environment. Similarly, Usman et al. (2021) assessed the ICT-CO$_2$ interconnection in selected Asian nations using a dataset from 1990 to 2018. The investigators utilized the ARDL approach, and their empirical outcomes unveiled that ICT plays a crucial role in enhancing the quality of the environment. Likewise, using STIRPAT and spatial econometric models, the research Sun and Kim (2021) using datasets between 2000 and 2017 reported that ICT mitigates CO$_2$ in China. Moreover, the research of Purewal and Haini (2021) on the ICT-CO$_2$ nexus in ASEAN economies using data from 1996 to 2019 disclosed that an upsurge in ICT in the selected nations contributes to a decrease in deterioration of the environment. Furthermore, using data from 1995–2018, Wang and Xu (2021) explored the association between internet usage and CO$_2$ in 70 countries and their outcome disclosed that the decrease in CO$_2$ emissions in the selected 70 nations is due to an increase in internet usage. Likewise, Liu et al. (2021) scrutinized the ICT-CO$_2$ interconnectedness in 33 Asian nations from 2000 to 2015, and the research finding concludes that a decrease in CO$_2$ is attributed to an upsurge in ICT in the 70 nations selected. Likewise, the research of Ahmed and Le (2021) on the association between ICT and CO$_2$ in 6 ASEAN nations using CUP-FM long-run estimator disclosed that ICT lower CO$_2$. Moreover, using GMM, Chatti Chatti (2020) used a dataset between 2002 and 2014 for 43 countries to assess the nexus between ICT and environmental quality and their finding disclosed that ICT enhances the quality of the environment. Moreover, the research of N'dri et al. (2021) in developing countries revealed that a surge in ICT enhances the quality of the environment. Likewise, the study of Ramzan et al. (2022) reported that ICT could predict CO$_2$. Similarly, the study of Chatti and Majeed (2021) reported that ICT plays a vital role in enhancing the quality of the environment in 46 nations using a dataset between 1998 and 2016. Kim (2021) assessed the association between CO$_2$ and ICT in South Korea using a dataset from 1990 to 2016 and the empirical outcome disclosed that ICT does not have a substantial influence on CO$_2$.

On the flip side, some studies established a positive ICT-CO$_2$ association. For instance, in a panel of rising nations, Danish et al. (2018) found that ICT damages the environment. They did imply, nevertheless, that

ICT combined with a high income enhances the environment. In the case of Africa, Asongu & Le Roux (2017) found that ICT, as defined by internet and mobile and mobile usage, increases CO$_2$; however, ICT also aids in reducing the negative ecological consequences of FDI and trade. Using the GMM approach, Asongu (2018) gave a similar perspective in the same region. The outcomes corroborated prior research that showed that growing ICT increases CO$_2$ emissions, although mobile phones and trade lower CO$_2$. Similarly, Avom et al. (2020) found that ICT increases emissions in the SSA area both indirectly and directly via energy usage. The research of Lee and Brahmasrene (2014), which examined panel data from the period between 1991 and 2009 for the ASEAN area, provided evidence supporting the theory that ICT has a detrimental effect on the environment. Nonetheless, their analysis had several flaws, including the use of first-generation unit root methodologies, outdated data, as well as cointegration and long-run approaches that did not account for CD and homogeneity. ICT boosts emissions in the G7 nations, but trade decreases emissions and the interplay of FDI and ICT also mitigates CO$_2$ (Raheem et al., 2020).

Considering the aforementioned research, it is clear that ICT is a two-edged sword that can be positive or negative and its impacts vary depending on the amount of ICT penetration in a nation, the methodology utilized, and the timeframe studied. Moreover, there is no research in the literature in the context of the top 10 ICT countries. While there is no agreement on the interrelationship between ICT and CO$_2$, the following hypothesis is drafted:

Hypothesis 1. ICT will reduce carbon emissions, thereby improving the quality of the environment

3. Data and methodology

3.1. Data

In order to capture the effect of information communication technology (ICT) on CO$_2$ emissions (CO$_2$), we utilized the top 10 ICT nations[1] (South Korea, Iceland, Switzerland, Denmark, Netherlands, Norway, Luxembourg, Japan and Sweden). The dataset for this empirical analysis spanned between 1986Q1 and 2019Q4. The data for ICT for the investigated countries are not available before 1985, which limits our study timeframe to the period between 1986 and 2019. The dataset for ICT was obtained from the database of the World Bank, while CO$_2$ data was gathered from the database of British Petroleum. ICT and CO$_2$ are measured as mobile cellular subscriptions (per 100 people) and CO$_2$ metric tons per capita, respectively. Table 1 reports the descriptive statistics for ICT and CO$_2$ for all the top 10 ICT nations. Figure 2 presents the analysis flow.

3.2. Methodology

In this research, in order to assess the effect of information communication technology (ICT) on CO$_2$ emissions (CO$_2$) in the top 10 ICT nations, we applied non-parametric approaches (quantile-on-quantile regression and Granger quantile causality). Furthermore, the QQR approach includes the advantages of both non-parametric and quantile regression methods (Alola et al., 2021; Sharif et al., 2021). It regresses the ICT quantiles on CO$_2$ to assess the model's asymmetry and spatial features over time (Sharif et al., 2020). We employed the quantile Granger causality test provided by (Troster et al., 2018) to detect the asymmetric causal interrelationship between variables under examination over the specified bandwidth parameter h = 0.05 as a complement to the QQR technique. The Quantile Granger causality and QQR techniques are briefly discussed in this section.

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[1] https://www.itu.int/en/ITU-D/Statistics/Documents/publications/misr2017/MISR2017_Volume2.pdf.

Table 1. Descriptive statistics.

	CO$_2$ Emissions							
	Mean	Max	Min	SD	Skewness	Kurtosis	JB	Prob
Denmark	9.750	14.414	5.287	2.216	-0.362	2.238	6.267	0.044
Japan	9.436	10.289	7.258	0.726	-1.563	4.836	74.500	0.000
Iceland	67.849	122.462	0.647	47.650	-0.373	1.349	18.589	0.000
Luxemburg	22.630	32.383	15.549	4.675	0.390	2.464	5.080	0.079
Netherland	10.535	11.737	8.918	0.672	-0.455	2.135	8.921	0.012
Norway	8.932	9.815	7.705	0.616	-0.231	1.624	11.933	0.003
South Korea	9.167	12.444	4.410	2.355	-0.467	2.143	9.108	0.011
Sweden	5.899	7.511	4.183	0.954	-0.518	1.961	12.187	0.002
Switzerland	69.174	136.854	0.024	54.681	-0.131	1.309	16.599	0.000
UK	8.812	10.647	5.401	1.559	-0.909	2.418	20.656	0.000
	Information and communication technology (ICT)							
Denmark	70.750	130.824	0.999	51.336	-0.235	1.330	17.047	0.000
Japan	9.927	12.358	7.165	1.280	-0.568	2.675	7.922	0.019
Iceland	61.922	149.070	0.067	49.237	0.113	1.677	10.213	0.006
Luxemburg	79.749	157.685	0.076	62.804	-0.237	1.258	18.464	0.000
Netherland	66.087	128.715	0.082	52.588	-0.213	1.267	18.045	0.000
Norway	68.037	116.207	1.790	44.925	-0.408	1.425	17.825	0.000
South Korea	60.089	136.236	0.017	48.137	-0.073	1.454	13.657	0.001
Sweden	72.723	129.595	1.099	49.432	-0.311	1.409	16.537	0.000
Switzerland	5.899	7.511	4.183	0.954	-0.518	1.961	12.187	0.002
UK	68.817	121.811	0.166	52.045	-0.281	1.259	18.976	0.000
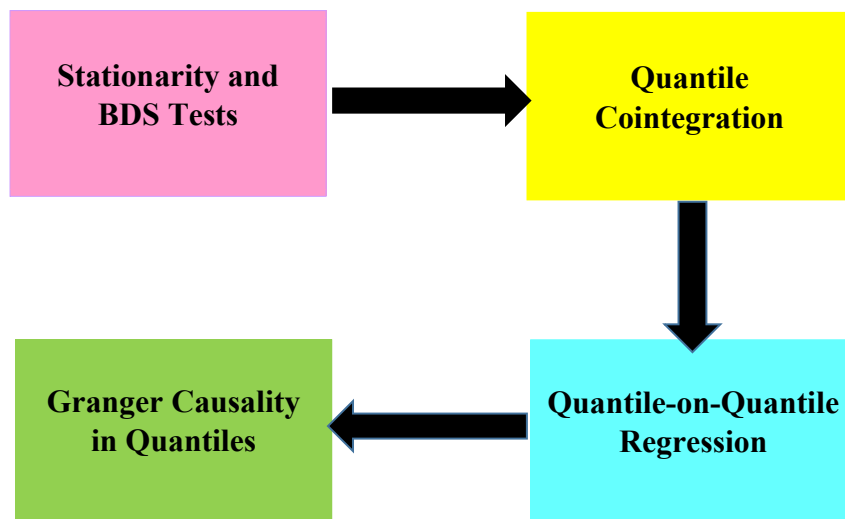
Figure 2. Flow of analysis.

3.3. Quantile-on-quantile regression

As previously stated, the current investigation adopts the Quantile-on Quantile (QQ) approach in accordance with the description and guidelines provided by (Sim and Zhou 2015). This approach, also known as the modification of the conventional quantile regression approach, allows for the evaluation of the impacts of the quantile of one parameter over the other. Furthermore, it is a blend of two processes: first, quantile regression, in which the approach examines the influence of a parameter on the quantiles of another parameter, while the second, as to do with the estimating in a non-parametric process. The quantile regression analysis, introduced by Bassett and Koenker (1978) is an improved extension of classic OLS-based regression analysis wherein the estimate of one variable is paled in comparison to the estimate of another parameter, although the Quantile regression can clarify more fluctuation of the quantiles and thus allows statisticians to anticipate with minimal errors.

Furthermore, standard regression, as explained and advocated by Stone (1977) and Cleveland (1979), consolidates the dimension of the feature in order to match a linear regression framework, hence reducing predictive capacity. On the contrary, whenever the quantiles of a parameter are evaluated to the quantiles of another variable, as permitted by the QQ approach, the predictive potential improves as more variance among the components is addressed. According to the study's goal, the non-parametric QQR analysis is depicted as follows:

$$CO_{2t} = \beta^{\theta} ICT_t + \varepsilon_t^{\theta} \tag{1}$$

Where: ICT and CO$_2$ stands for information communication technology and carbon emission while t stands for time. Moreover, θ indicates the conditional distribution of CO$_2$ in the qth quantile, and ε indicates the error term of the quantile wherein the conditional qth is exactly zero. Finally, β^{θ} depicts a function that is unknown due to inadequate of

knowledge on the association between CO_2 and ICT. The QQ approach is based on the aggregate behavior of the constructs when assessing the association between two variables. Also, in a situation where there are any disturbances in ICT, either favorable or unfavorable, they will have a proportional impact on CO_2. For instance, the pattern of disruptions in ICT can be either favorable or unfavorable, and in such a case, the CO_2 may respond properly or asymmetrically. Furthermore, because β^θ is uncertain, the estimated first-order Taylor advanced function is indicated in Eq. (2).

$$\boldsymbol{\beta}^\theta(\mathbf{ICT}_t) \approx \boldsymbol{\beta}^\theta(\mathbf{ICT}^t) + \boldsymbol{\beta}^{\theta'}(\mathbf{ICT}^t)(\mathbf{ICT}_t - \mathbf{ICT}^t). \qquad (2)$$

Where: $\beta^{\theta'}$ indicates the partial derivative of $\beta^\theta(ICT_t)$ in relation of ICT_t that is referred to as the marginal influence, which denotes the standard regression analysis' slope. Also, it is observed in Eq. (2) that the indicators were indexed doubly, i.e., $\beta^\theta(ICT^t)$ and $\beta^{\theta'}(ICT^t)$ in relation to θ and τ. However, the function of θ and ICT^t are $\beta^\theta(ICT^t)$ and $\beta^{\theta'}(ICT^t)$. However, ICT^t is a function of t, that reveals that $\beta^\theta(ICT^t)$ and $\beta^{\theta'}(ICT^t)$ can be expressed as Eq. (3):

$$\boldsymbol{\beta}^\theta(\mathbf{ICT}_t) \approx \boldsymbol{\beta}_\theta(\boldsymbol{\theta}, \boldsymbol{\tau}) + \boldsymbol{\beta}_1(\boldsymbol{\theta}, \boldsymbol{\tau})(\mathbf{ICT}_t - \mathbf{ICT}^t). \qquad (3)$$

In addition, by substituting Eq. (2) for into Eq. (1), the subsequent equation is displayed in Eq. (4):

$$\boldsymbol{CO}_{2t} = \underbrace{\boldsymbol{\beta}_0(\boldsymbol{\theta}, \boldsymbol{\tau}) + \boldsymbol{\beta}_1(\boldsymbol{\theta}, \boldsymbol{\tau})(\mathbf{ICT}_t - \mathbf{ICT}^\tau)}_{(*)} + \boldsymbol{\mu}_t^\theta \qquad (4)$$

In Eq. (4) (*) indicates the qth provisional quantile of CO_2. The provisional quantile differs from the ordinary conditional quantile in that the variables are indexed doubly, i.e., β_0 and β_1 in regards of q and t, respectively, and it reflects the qth quantile of CO_2 with the tth quantile of ICT. There is a potential of a discrepancy in variables between the qth quantile of CO_2 and the tth quantile of ICT. Furthermore, a linear relationship between parameters is expected at all times. As a result, Eq. (3) analyzes the model's aggregate interconnections depending upon that distribution-based reliance of the researched variables. Furthermore, in Eq. (4), ICT_t and ICT^t should be substituted by their computed equivalents, $\widehat{ICT_t}$ and $\widehat{ICT^t}$. As a result, the evaluations from the localized linear regression analysis of the variables β_0 and β_1, which are evaluated by β_0 and β_1 that may be computed as the minimization issue illustrated in Eq. (5):

$$\boldsymbol{Min}_{\delta_0 \delta_1} \sum_{t=1}^n \boldsymbol{\sigma}_\varnothing \left[\boldsymbol{CO}_{2t} - \boldsymbol{\delta}_0 - \boldsymbol{\delta}_1(\widehat{ICT_t} - \widehat{ICT^\tau})\right] \times \boldsymbol{L}\left[\frac{\boldsymbol{M}_n(\widehat{ICT_t}) - \boldsymbol{\tau}}{\boldsymbol{h}}\right] \qquad (5)$$

Where: $\sigma_\varnothing$ indicates the loss of the quantile, which is explained as $\sigma_\varnothing(u) = u(\theta - 1(u < 0))$, L (*) is the kernel function and the kernel parameter bandwidth is indicated as h. The Gaussian kernel is employed in this research to determine the weight of the neighborhood observations of CO_{2t}, which is among the most commonly adopted, prominent, and discussed kernel functions, due to its ease of computation and processing. The advantage of this kernel is that it is symmetrical as it reaches zero, and the distant samples are assigned minimal weights. In this current research, the previously stated weights and the distance between the function's distributions of $\widehat{FGLO_t}$ are negatively proportionate and are symbolized as $F_n(\widehat{ICT_t}) = \frac{1}{n}\sum_{k-1}^n I(\widehat{ICT_k} > \widehat{ICT_t}$, wherein the reward of the stochastic process that will come to terms with the quantile ICT_t is symbolized by t. Moreover, choosing bandwidth is critical when utilizing non-parametric approaches. This is because it controls the smoothing of the computed results by determining the magnitude whereby the neighborhood estimates fluctuate around the specified position.

Furthermore, if the bandwidth is set to a little amount, it will result in more variation, whilst setting it to a big value would result in prejudice. As a result, the values that fall between variance and biasness must be chosen while determining the bandwidth. Following the suggestions by Sim and Zhou (2015), the current investigation used the bandwidth parameter value of h = 0.05.

3.4. Granger causality in quantiles

The present research contributes to the literature on the ICT and CO_2 nexus by applying the novel Granger causality in the quantiles approach proposed by Troster et al. (2018). According to Granger (1969), if Xi cannot forecast Zi, it means that Xi does not cause series Zi. Assume vector $(\mathcal{M}_i = \mathcal{M}_i^{\mathcal{Z}}, \mathcal{M}_i^{\mathcal{X}}) \in \Re^e$, $e = o + q$, with $\mathcal{M}_i^{\mathcal{X}}$ is the previous evidence set of $\mathcal{X}_i \mathcal{M}_i^{\mathcal{X}} = (\mathcal{X}_{i-1}, \ldots \mathcal{X}_{i-q},)' \in \Re^q$. Besides, H_o hypothesis is depicted as follows:

$$\mathcal{H}_o^{\mathcal{X} \to \mathcal{Z}} : \mathcal{F}\mathcal{Z}\left(\mathcal{Z}\big|\mathcal{M}_i^{\mathcal{Z}}, \mathcal{M}_i^{\mathcal{X}}\right) = \mathcal{F}\mathcal{Z}\left(\mathcal{Z}\big|\mathcal{M}_i^{\mathcal{Z}}\right)\text{for all } \mathcal{X} \in \Re, \qquad (6)$$

$\mathcal{F}\mathcal{Z}(.\big|\mathcal{M}_i^{\mathcal{Z}}, \mathcal{M}_i^{\mathcal{X}})$ is regarded as the conditional scattering function of Zi as long as $\mathcal{M}_i^{\mathcal{X}}, \mathcal{M}_i^{\mathcal{z}}$ in the ambit of null hypothesis illustrated by Eq. (6). The research of Troster (2018) was followed in assessing the Dt test, which identifies the framework of QA (•) for all $\pi \in \Gamma \subset [0,1]$, upon Granger causality null hypothesis. The same can be defined below:

$$QAR(1) : m_1\left(\mathcal{M}_i^{\mathcal{Z}}\big|\partial(\pi)\right) = \lambda 1(\pi) + \lambda 2(\pi)\mathcal{Z}_{i-1} + \mu t \psi_x^{-1}(\pi) \qquad (7)$$

Where the values $\partial(\pi) = \lambda 1(\pi), \lambda 2(\pi)$and μt re-assessed by the probability of supreme in quantiles grid space that is equal, and $\psi_{\mathcal{X}}^{-1}(.)$ is the opposing of a normal orthodox dispersal function. By evaluating the QAF model in Eq. (7) with the lagged parameter to another parameter, we can further adjust the causality sign between the variables. Eq. (8) presents the QAR (1):

$$\mathcal{Q}_\pi^{\mathcal{Z}} = \left(\mathcal{Z}_i\big|\mathcal{M}_i^{\mathcal{Z}}, \mathcal{M}_i^{\mathcal{X}}\right) = \lambda 1(\pi) + \lambda 2(\pi)\mathcal{Z}_{i-1} + \eta(\pi)\mathcal{X}_{i-1} + \mu t \psi_{\mathcal{X}}^{-1} \qquad (8)$$

4. Findings and discussion

The current research commenced by assessing the stationarity attribute of the variables of investigation (ICT and CO_2). In doing so, we applied both PP and ADF unit toot tests to catch ICT and CO_2 stationarity features. The ADF and PP outcomes are depicted in Table 2 and the outcomes unveiled that all the variables are I (1) variables. Furthermore, we check the nonlinearity characteristics of ICT and CO_2 in the selected nations using the BDS test initiated by Broock et al. (1996). Table 3 reports the BDS result with the outcomes suggesting that all the variables are non-linear. This outcome corroborates the Jarque-Bera outcomes in Table 2. Based on this understanding, using linear approaches such as CCR, DOLS, FMOLS, ARDL, POLS, VECM and many more will produce misleading results. Therefore, the current research utilized non-parametric approaches (quantile-on-quantile and Granger causality in quantiles) to assess the interconnectedness between ICT and CO_2 in the selected nations.

After the nonlinearity characteristics have been established, we proceed to assess the non-linear cointegration between ICT and CO_2 in the top 10 ICT nations. In doing so, we use the quantile cointegration suggestion by Xiao (2009) to catch the long-run interconnectedness between ICT and CO_2. Table 4 reports the quantile cointegration outcomes and the outcome disclosed that the null hypothesis of "no cointegration" is rejected for all the top 10 ICT nations. Thus, in long-run evidence of cointegration is supported in South Korea, the United Kingdom, Sweden, Iceland, Japan, Norway, Luxemburg, Denmark, Netherland, and Switzerland.

Table 2. ADF and PP Unit root Tests.

	ICT				CO2			
	ADF		PP		ADF		PP	
	Level	Δ	Level	Δ	Level	Δ	Level	Δ
Denmark	-1.499	-5.807*	-0.874	-5.895*	-1.987	-3.794**	-2.177	-6.282*
Japan	-3.496**	-4.131*	-3.014	-3.965**	-2.995	-4.453*	-1.396	-5.451*
Iceland	-1.908	-3.758**	-1.055	-3.233***	-0.269	-3.799**	-0.311	-4.829*
Luxemburg	-0.548	-3.848*	-0.959	-5.495*	-4.561*	-2.813	-2.006	-4.857*
Netherland	-2.253	-4.318*	-1.389	-3.715**	-3.183	-3.640**	-2.938	-9.254*
Norway	-1.697	-4.567*	-1.615	-4.021*	-1.036	-3.830**	-0.154	-9.002*
South Korea	-2.106	-5.678*	-2.088	-5.054*	-1.645	-3.550**	-1.651	-5.259*
Sweden	-2.148	-5.390*	-0.557	-3.665**	-2.100	-4.484*	-1.959	-6.528*
Switzerland	-2.670	-4.484*	-1.959	-6.528*	-2.123	-4.191*	-1.0781	-4.770*
UK	-1.497	-5.695*	-0.794	-3.971**	-1.668	-3.619**	-1.319	-9.570*

Note: 1%, 5% and 10% level of significance are denoted by *, ** and *** respectively.

Table 3. BDS test outcomes.

	Denmark	Japan	Iceland	Luxemburg	Netherland	Norway	South Korea	Sweden	Switzerland	UK
	Information and Communication Technology (ICT)									
M2	49.785*	48.947*	48.947*	47.080*	47.972*	45.055*	49.734*	49.744*	39.647*	47.371*
M3	53.240*	52.383*	52.383*	50.149*	51.388*	48.333*	52.991*	53.429*	41.714*	50.808*
M4	57.644*	56.760*	56.761*	54.037*	55.759*	52.468*	57.215*	58.126*	44.533*	55.172*
M5	64.097*	63.132*	63.130*	59.718*	62.124*	58.469*	63.404*	64.916*	48.870*	61.499*
M6	73.001*	71.987*	71.987*	67.495*	70.860*	66.575*	71.910*	74.216*	55.003*	70.170*
	Carbon Emissions (CO2)									
M2	36.011*	31.418*	31.418*	34.671*	40.126*	45.486*	42.126*	39.647*	49.558*	32.754*
M3	37.544*	33.175*	33.175*	36.411*	41.386*	48.098*	44.704*	41.719*	53.146*	34.419*
M4	39.723*	35.448*	35.448*	38.581*	43.416*	51.585*	47.948*	44.533*	57.734*	36.758*
M5	43.244*	38.764*	38.764*	41.887*	46.958*	56.909*	52.763*	48.870*	64.409*	40.377*
M6	48.424*	43.414*	43.414*	46.491*	52.059*	64.330*	59.432*	55.003*	73.574*	45.617*

Note: 1% level of significance is denoted by *.

Table 4. Quantile cointegration test outcomes.

Model	Coefficient	$Sup_\tau|V_\pi(\tau)|$	CV1	CV5	CV10
Denmark	β	7841.97	4729.57	3898.76	2771.59
CO2t Vs ICTt	α	716.166	418.524	324.792	101.987
Japan	β	3286.58	2899.14	2015.44	1839.67
CO2t Vs ICTt	α	425.797	290.112	192.391	108.943
Iceland	β	3276.185	2181.316	1147.878	896.265
CO2t Vs ICTt	α	342.724	229.026	187.467	103.475
Luxemburg	β	8455.78	5145.71	4798.92	2114.56
CO2t Vs ICTt	α	779.996	437.565	389.475	151.308
Netherland	β	9294.67	7437.56	4924.2	2140.58
CO2t Vs ICTt	α	864.225	569.866	245.119	164.957
Norway	β	4313.07	3251.43	2487.18	1585.43
CO2t Vs ICTt	α	401.132	294.056	149.856	1063.028
South Korea	β	9127.132	7360.05	5614.38	3171.36
CO2t Vs ICTt	α	884.933	642.264	426.440	218.022
Sweden	β	4515.06	3491.764	2746.51	1896.34
CO2t Vs ICTt	α	506.058	437.608	297.454	137.868
Switzerland	β	2647.69	1649.71	1274.19	807.178
CO2t Vs ICTt	α	240.777	173.827	101.513	82.2206
UK	β	4844.45	3833.91	2705.85	1239.31
CO2t Vs ICTt	α	434.874	297.177	191.267	107.888

4.1. Quantile-on-quantile outcomes

The current research assessed the effect of ICT on CO_2 emissions after the long-run cointegration between ICT and CO_2 had been established. In doing so, we used the novel quantile-on-quantile regression (QQR) approach initiated by Sim and Zhou (2015). Figure 3 shows the effect of ICT on CO_2. Figure 3a presents the influence of ICT on CO_2 in Denmark. In all quantiles (0.1–0.95), we observed that ICT has a significant and negative effect on CO_2 in Denmark in all quantiles (0.1–0.95) of both ICT and CO_2; however, in the quantiles of (0.10–0.30 and 0.45–0.65) of CO_2 and all tails (0.1–0.95) of ICT, the effect of ICT on CO_2 is negative and weak. In summary, we observe a negative ICT-CO_2 interconnection in all tails (0.1–0.95) of both ICT and CO_2. The influence of ICT on CO_2 in Iceland is reported in Figure 3b. In all quantiles (0.1–0.95) of both ICT and CO_2, we observe a positive ICT-CO_2 interconnection suggesting that in all quantiles (0.1–0.95), the positive effect of ICT on CO_2 is dominant. However, in the extreme tail (0.75–0.95) of CO_2 and the higher tail (0.70–0.95) of ICT, the positive effect of ICT on CO_2 is observed. Generally, the positive effect of ICT on CO_2 is observed in all tails (0.1–0.95) of both ICT and CO_2.

Figure 3c presents the effect of ICT on CO_2 in Japan. In the lower tail (0.10–0.40) of both ICT and CO_2, we observe a negative ICT-CO_2 association; however, from 0.50-0.60, a positive interconnectedness between ICT and CO_2 can be observed. Furthermore, in the upper tails (0.65–0.80)
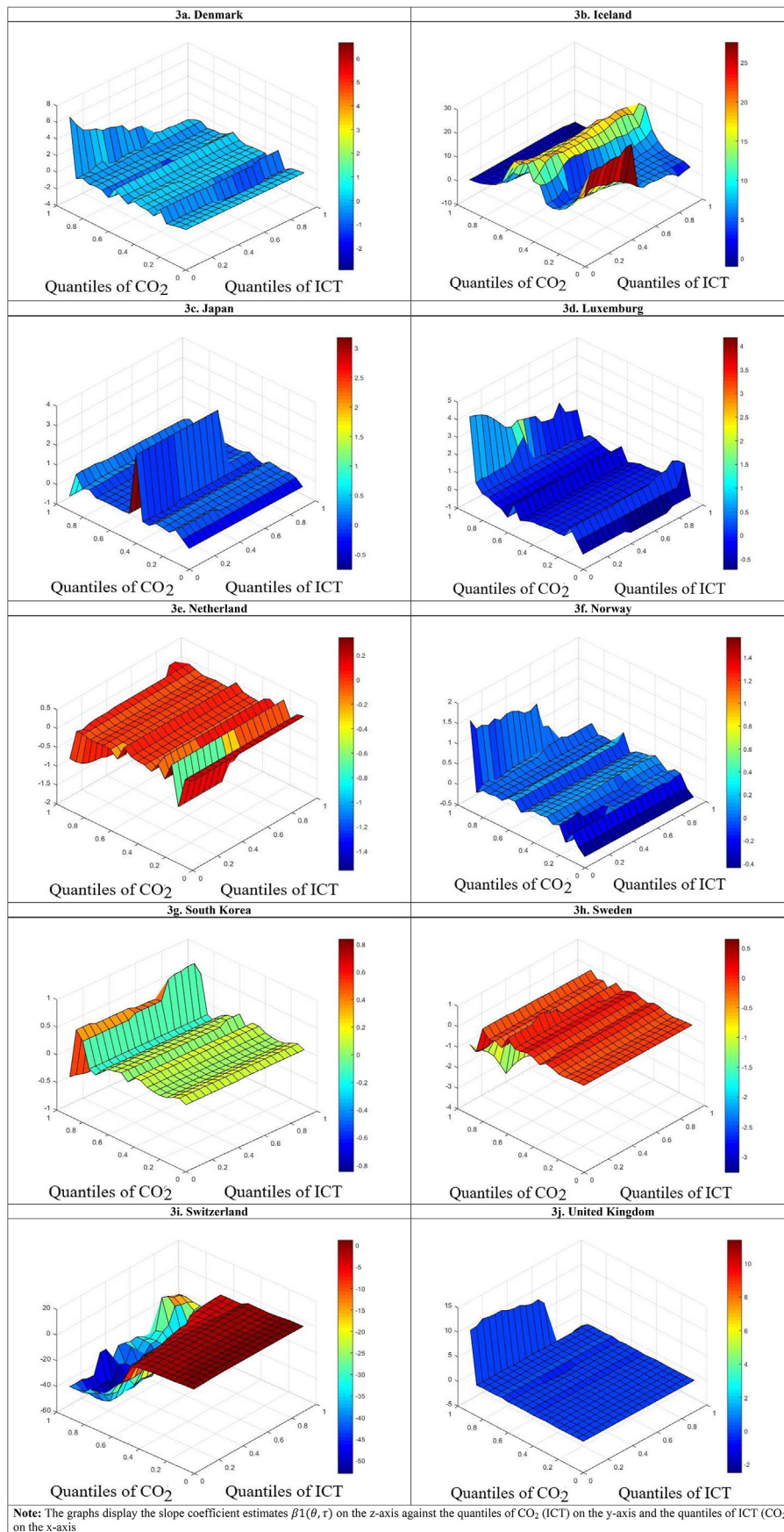
Note: The graphs display the slope coefficient estimates $\beta 1(\theta, \tau)$ on the z-axis against the quantiles of CO_2 (ICT) on the y-axis and the quantiles of ICT (CO_2) on the x-axis

Figure 3. (a–j). Impact of ICT on CO_2 emissions.

of both ICT and CO_2, the influence of ICT on CO_2 is negative and weak. In summary, the negative effect of ICT on CO_2 is negative and weak. Figure 3d presents the effect of ICT on CO_2 in Luxemburg. In the lower, middle and upper tails (0.1–0.95) of the combination of both ICT and CO_2, the negative influence of ICT on CO_2 is evident, although the negative effect decreases as we move to the higher tail. In summary, we conclude that the influence of ICT on CO_2 is negative across all quantiles (0.1–0.95). The effect of ICT on CO_2 for the Netherlands is presented in Figure 3e. In the lower and middle quantiles (0.1–0.65) of CO_2 and ICT, the negative and weak effect of ICT on CO_2 is evident; however, in the higher quantile (0.70–0.90), the effect of ICT on CO_2 is positive and weak.

Figure 3f shows the effect of ICT on CO_2 in Norway. In the extreme tails (0.1–0.40) and (0.70–0.90), the effect of ICT on CO_2 is negative; however, in the middle quantiles (0.40–0.65) of CO_2 and ICT, the effect of ICT on CO_2 is weak and positive. Figure 4g discloses the effect of ICT on CO_2 in South Korea. In the lower and middle tails (0.1–0.60) of both CO_2 and ICT, a positive and weak effect of ICT on CO_2 is evident; however, in quantiles (0.70–0.80) of CO_2 and all quantiles (0.1–0.95) of ICT, we observe a weak and negative effect of ICT on CO_2. Furthermore, in the extreme tail (0.85–0.95) of CO_2 emissions and the lower and middle tails (0.1–0.65) of ICT, the influence of ICT on CO_2 is weak and positive. Figure 3h shows the influence of ICT on CO_2 in Sweden. In the lower and middle tails (0.1–0.60), the positive and insignificant influence of ICT on CO_2 is dominant; however, in the extreme tails (0.80–0.95), the negative effect of ICT on CO_2 is observed. Thus, in the majority of the quantiles, the positive influence of ICT on CO_2 is dominant.

The influence of ICT on CO_2 emissions in Switzerland is depicted in Figure 3i. In all the quantiles (0.1–0.95), the influence of ICT on CO_2 is negative and significant; however, in the higher tails (0.65–0.95) of CO_2 and all quantiles (0.1–0.95) of ICT, the negative influence of ICT on CO_2 is more pronounced. This illustrates that ICT influences CO_2 negatively in the majority of the quantiles. Lastly, Figure 3j presents the effect of ICT on CO_2 in United Kingdom. In all quantiles (0.1–0.95) of both CO_2 and ICT, the negative effect of ICT on CO_2 is dominant, suggesting that ICT lessens CO_2 in the United Kingdom.

4.2. Robustness check outcomes for QQR approach

The present research checks the validity of the quantile-on-quantile (QQR) by applying the quantile regression (QR). The QR model is based on predicting the θth quantile of ICT on CO_2. As a corollary, the standard QQ method's parameters are simply indexed by θ. The QQR approach, on the flipside, examines the ICT θth quantile on the CO_2 τth quantile. As a result, the characteristics of the QQR method are indexed by both and, providing more extensive information than the standard QR method. As a result, we can simply retrieve the estimates of the classic QR method from the QQR method. The QR technique parameters, which are indexed by θ, can be obtained by taking the simple average of the QQR estimation parameters along τ. The slope coefficient of the QR model, represented by γ1(θ), which assesses the influence of ICT on CO_2 distributions, can be computed as follows:

$$\gamma_1 \equiv \overline{\widehat{\beta_1(\theta)}} = \frac{1}{S}\sum_\tau \widehat{\beta_1}(\theta, \tau) \tag{9}$$

Where: the quantiles number S = 19 and $\tau = [0.05, 0.10, ..., 0.95]$ is considered.

Figure 4 (a-j) backs up our previous QQR method results (see Figures 3 (a-j)). According to the graphs, the slope coefficients average estimates of QQR regression estimations behave similarly to regular QR assessment. In a nutshell, these outcomes confirm the QQR technique's outcomes. Our empirical findings, as revealed in Figures 4 (a-j), indicate

that the relationship between ICT and CO_2 has broad heterogeneity and variance across the selected nations, requiring individual attention when formulating environmental and ICT policies in the top ICT nations.

4.3. Granger causality in quantile outcomes

The present research applied the novel Granger causality in quantiles suggested by Troster (Troster et al., 2018) to capture the causality between ICT and CO_2 in the top 10 ICT economies. The outcomes of the causality are reported in Table 5. For Denmark, at a 5% level of significance in quantiles (0.05–0.20 and 0.50–0.80), ICT Granger cause CO_2. On the flip side, there is causality running from CO_2 to ICT in quantiles (0.2–0.3, 0.80 and 0.90). Thus, bidirectional causality between ICT and CO_2 is affirmed. For Iceland, ICT Granger cause CO_2 in quantiles (0.20, 0.50–0.70, 0.80 and 0.90). On the other hand, CO_2 Granger cause ICT in quantiles (0.10, 0.20, and 0.50–0.80). In summary, feedback causality between ICT and CO_2 is affirmed in Iceland.

For Japan, at a 5% level of significance Granger causality from ICT to CO_2 is confirmed in quantiles (0.05–0.30, 0.60–0.70 and 0.95). On the flip side, there is no support for causality from CO_2 to ICT considering all quantiles and each quantile. Therefore, there is one-way causality from ICT to CO_2 for Japan. For Luxemburg, at a significance level of 5%, there is causality from ICT to CO_2 in quantiles (0.10, 0.70 and 0.95). On the flip side, no support for causality from CO_2 to ICT at a 5% level of significance. Therefore, for Iceland, there is unidirectional causality from ICT to CO_2. For the Netherlands, ICT Granger cause CO_2 in quantiles (0.20–0.30, and 0.8–0.90). In addition, no support for causality from CO_2 to ICT. Therefore, unidirectional causality is affirmed in the case of the Netherlands.

For Norway, in quantiles (0.1–0.2, and 0.6–0.80), ICT Granger cause CO_2 at a 5% significance level. On the other hand, CO_2 Granger cause ICT in quantiles (0.2, 0.6–0.80). Therefore, a feedback causality is established between ICT and CO_2 for the case of Norway. For South Korea, ICT Granger cause CO_2 in quantiles (0.4–0.70). On the other hand, CO_2 Granger cause ICT in quantiles (0.10 and 0.60–0.70). Therefore, there is evidence of two-way causality at the majority of the quantile for South Korea. For Sweden, ICT Granger CO_2 in quantiles (0.20, 0.40 and 0.60–0.70). On the flipside, CO_2 Granger cause ICT in quantiles (0.10, 0.30, 0.7 and 0.95) at a 5% level of significance. Therefore, feedback causal interconnectedness between CO_2 and ICT is established for South Korea.

For Switzerland, at all quantiles (0.05–0.40 and 0.80–0.95), at a 5% level of significance Granger causality from ICT to CO_2 is confirmed. Furthermore, no support of causality was found from CO_2 to ICT. Lastly, For the United Kingdom, at quantiles (0.05–0.20, 0.40–0.70 and 0.95), ICT Granger CO_2 at 5% significance level. Furthermore, support was established for causality running from CO_2 to ICT. Therefore, on-way causality was established running from CO_2 to ICT.

4.4. Discussion of findings

This section presents a discussion of the findings based on the methodologies applied. The outcomes of the BDS test validate the use of non-parametric approaches (quantile-on-quantile regression and Granger causality in quantiles). The outcomes of the QQR disclosed that in the majority of the quantiles, ICT exerts a negative effect on CO_2 for Denmark, Japan, Luxemburg, Norway, Sweden, Switzerland, and the United Kingdom. This implies that in Denmark, Japan, Luxemburg, Norway, Sweden, Switzerland, and the United Kingdom, ICT abates CO_2 emissions. This finding indicates that the use of ICT significantly improves the quality of the environment. As a result, the use of smart electric products, smart grids and home automation technologies not only saves energy but also improves the quality of the environment. The
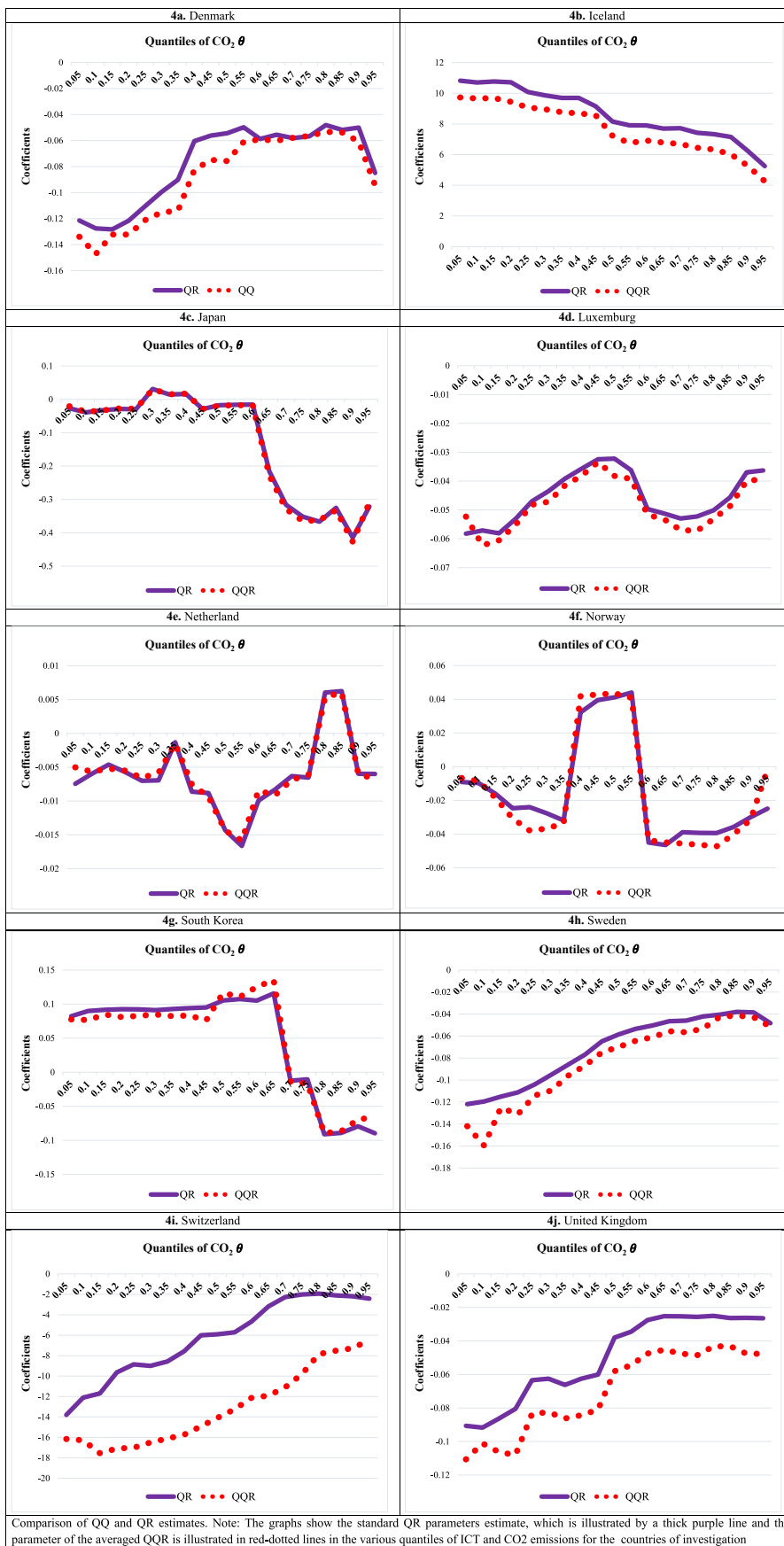
Comparison of QQ and QR estimates. Note: The graphs show the standard QR parameters estimate, which is illustrated by a thick purple line and the parameter of the averaged QQR is illustrated in red-dotted lines in the various quantiles of ICT and CO2 emissions for the countries of investigation

Figure 4. (a–j): Comparison of QQR and QR estimates for the impact of ICT on CO_2 emissions.

Table 5. Granger causality in quantiles outcomes.

Country		Quantiles										
		0.05	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9	0.95
Denmark	ICT → CO$_2$	0.082	0.003*	0.003*	0.745	0.328	0.002*	0.010*	0.010*	0.030*	0.316	0.694
	CO$_2$ → ICT	0.449	0.194	0.010*	0.020*	0.143	0.551	0.010*	0.051	0.010*	0.010*	0.214
Iceland	ICT → CO$_2$	0.010*	0.388	0.010*	0.214	0.010*	0.051	0.347	0.031*	0.010*	0.327	0.010*
	CO$_2$ → ICT	0.010*	0.571	0.010*	0.310*	0.531	0.010*	0.010*	0.010*	0.010*	0.153	0.276
Japan	ICT → CO$_2$	0.010*	0.010*	0.010*	0.041*	0.122	0.224	0.010*	0.010*	0.327	0.102	0.041*
	CO$_2$ → ICT	0.469	0.426	0.589	0.738	0.867	0.133	0.221	0.113	0.412	0.469	0.194
Luxemburg	ICT → CO$_2$	0.357	0.020*	0.051	0.031*	0.184	0.592	0.112	0.010*	0.327	0.102	0.041*
	CO$_2$ → ICT	0.245	0.469	0.441	0.052	0.061	0.224	0.026*	0.310	0.721	0.121	0.194
Netherland	ICT → CO$_2$	0.201	0.422	0.010*	0.010*	0.053	0.764	0.274	0.020*	0.010*	0.041*	0.271
	CO$_2$ → ICT	0.214	0.112	0.051	0.031*	0.184	0.592	0.112	0.232	0.327	0.102*	0.051
Norway	ICT → CO$_2$	0.204	0.010*	0.010*	0.065	0.310	0.010*	0.010*	0.010*	0.020*	0.541	0.449
	CO$_2$ → ICT	0.041	0.051	0.010*	0.520	0.102	0.061	0.092	0.071	0.010*	0.173	0.408
South Korea	ICT → CO$_2$	0.551	0.480	0.516	0.120	0.010*	0.010*	0.010*	0.010*	0.143	0.888	0.520
	CO$_2$ → ICT	0.112	0.010*	0.410	0.310	0.531	0.980	0.010*	0.010*	0.582	0.728	0.745
Sweden	ICT → CO$_2$	0.045*	0.469	0.010*	0.010*	0.041*	0.224	0.010*	0.010*	0.010*	0.010*	0.194
	CO$_2$ → ICT	0.357	0.010*	0.051	0.031*	0.184	0.592	0.112	0.010*	0.327	0.102	0.041*
Switzerland	ICT → CO$_2$	0.010*	0.010*	0.010*	0.010*	0.010*	0.112	0.537	0.164	0.010*	0.010*	0.010*
	CO$_2$ → ICT	0.081	0.121	0.110*	0.263	0.091	0.643	0.384	0.051	0.650	0.544	0.546
United Kingdom	ICT → CO$_2$	0.011*	0.010*	0.010	0.054	0.656	0.021*	0.041*	0.011*	0.172	0.269	0.010*
	CO$_2$ → ICT	0.251	0.269	0.310	0.432	0.925	0.172	0.066	0.551	0.062	0.073	0.194

Table 5 unveils the sub-sampling p-values of the DT test. The log-difference of CO$_2$ emissions in a quarter is depicted by ΔCO$_2$t, and the log difference of ICT is illustrated by ΔICTt. * stands for significance level of 5%. The dismissal of the null hypothesis at the 5% significance level is illustrated by *.

research showed that ICT could aid in the reduction of air pollution such as e-news and reading online books instead of printed versions, using electronic mail instead of paper mail, utilizing food services online instead of hotels, shopping online instead of using physical markets, as well as online learning and online conferences instead of attending school. As a result, it can reduce fuel usage while also indirectly lowering pollution levels. In addition, the widespread use of ICT in daily life aids in energy conservation, such as the efficient use of smartphones, laptops, and other small ICT devices. As a result, the governments of Denmark, Japan, Luxemburg, Norway, Sweden, Switzerland, and the United Kingdom must devote more resources to delivering smart technology to the general public and raising knowledge about the use of ICT tools. The study of Chatti (2021) for 43 nations from 2002 to 2014 reported a similar result. Furthermore, the research of Ben Lahouel et al. (2021) that used a dataset between 1970 and 2018 for Tunisia reported similar findings by establishing a negative ICT-CO$_2$ interconnectedness.

Conversely, for the case of South Korea, Netherlands, and Iceland, in the majority of the quantiles, the effect of ICT on CO$_2$ is positive, suggesting that in these nations, an upsurge in ICT contributes to the degradation of the environment. Surprisingly, the actual findings have revealed the fallacy of the theory that ICT may improve the quality of the environment. In addition, this implies that excessive use of the Internet by users is damaging the environment with a significant amount of CO$_2$ emissions caused by electricity consumption. In the literature, this problem has been documented, with the outcomes indicating both an indirect and direct impact on CO$_2$. According to Irawan (2014), the usage of ICT has a negative impact on the environment as a result of GHG emissions. According to Palvia et al. (2018)Palvia et al. (2018), increased usage of the internet would result in an upsurge in electricity demand, resulting in higher emissions. Despite the fact that ICT is required to implement environmental rules, its use is unregulated (Sun and Kim, 2021). Furthermore, worldwide ICT usage, including computer equipment, generates 2% of global GHG emissions by utilizing more than 3.9 percent of global power (Malmodin et al., 2010). This suggests that ICT has a favorable impact on GHG emissions. Although ICT plays an important role in social and economic progress, it also has harmful effects

on the environment. In addition, the usage and installation of ICT equipment consume more energy. As a result of this rapid growth in the ICT sector, more energy is used, which is the primary source of CO$_2$ emissions. Previous studies by Salahuddin et al. (2018), Palvia et al. (2018), and Moyer & Hughes (2012) assessed the interconnectedness between CO$_2$ emissions and ICT and found that ICT use affects energy consumption, which subsequently increases CO$_2$ emissions.

Moreover, regarding the findings from the Granger causality in quantiles, ICT can significantly predict CO$_2$ for all the selected nations. Thus, policymakers in Denmark, Japan, Luxemburg, Norway, Sweden, South Korea, Netherlands, Iceland, Switzerland, and the United Kingdom should be cautious regarding the importance of ICT since it can increase (decrease) CO$_2$. Thus, policymakers in these nations should formulate policies towards the effective utilization of ICT.

5. Conclusion and policy direction

5.1. Conclusion

ICT has had an impact on the quality of the environment, much like all other modern technologies. Nevertheless, there is a debate among scholars and environmentalists as to whether ICT contributes to the degradation of the environment by consuming large amounts of energy and transmitting toxic materials during production or whether it significantly mitigates CO$_2$ emissions by minimizing the consumption of energy as a result of its efficient and smart role, particularly in the energy sector and more broadly in society. Therefore, the present study assesses the effect of ICT on CO$_2$ emissions in the top 10 ICT nations (Denmark, Japan, Luxemburg, South Korea, Netherlands, Iceland, Norway, Sweden, Switzerland, and the United Kingdom). The current paper utilizes non-parametric approaches (such as quantile-on-quantile regression and Granger causality in quantiles) to assess this interconnectedness. The outcomes of the BDS test for all the nations under investigation affirm the utilization of non-parametric approaches. Furthermore, the outcomes of the quantile-on-quantile (QQR) revealed interesting findings. Firstly, we observed that for the case of Denmark, Japan, Luxemburg, Norway,

Sweden, Switzerland, and the United Kingdom, ICT abates CO_2 emissions. This implies that the utilization of ICT in these nations enhances the quality of the environment. Secondly, for the case of South Korea, the Netherlands, and Iceland, in the majority of the quantiles, the effect of ICT on CO_2 emissions is positive, suggesting that in these nations, an upsurge in ICT contributes to the degradation of the environment. Moreover, the outcomes of the Granger causality in the quantiles approach unveiled that ICT and CO_2 can predict each other for the majority of the countries.

5.2. Policy suggestions

Based on the outcomes obtained, several policy suggestions are proposed. The results not only add to the current body of knowledge, but they also demand special consideration from policymakers in the countries involved. Firstly, Denmark, Japan, Luxemburg, Norway, Sweden, Switzerland, and the United Kingdom should encourage the development of the ICT industry in the low-carbon economy. Sustainable ICT should be adopted to guarantee that ICT equipment is used in an environmentally responsible manner and that the ICT sector continues to grow in the long run in Denmark, Japan, Luxemburg, Norway, Sweden, Switzerland, and the United Kingdom. Furthermore, sustainable ICT should also be used to improve carbon reduction and energy savings potential by optimizing other industries, including managing and monitoring energy usage in industrial production.

Secondly, in South Korea, Netherlands, and Iceland, a surge in ICT utilization contributes to the degradation of the environment, suggesting that ICT is not eco-friendly in these countries. Consequently, to make this industry more ecologically friendly, authorities in the aforementioned nations should attempt to encourage smart ICT products that aid in accomplishing efficient energy utilization. The adverse impacts of ICT usage on the ecosystem would decrease as these nations lower their heavy utilization of energy via the utilization of smart ICT devices. Furthermore, in order to reduce CO_2 emissions caused by growing energy consumption, these nations should reduce their reliance on non-renewable energy sources and focus on developing greener, cleaner alternatives, because ICT cannot minimize CO_2 on its own except if the energy it uses is greener and cleaner. As a result, South Korea, Netherlands, and Iceland should place greater emphasis on using ICT to reduce CO_2 and promote inclusive growth. In addition, authorities in these nations should enhance research and development (R&D) spending to aid in the development of environmentally-friendly ICT products. Furthermore, authorities should enact high levies on companies that create CO_2 and other greenhouse gases during the production process.

Future studies can investigate the nature of the interrelationship by exploring more complex interrelationships through consideration of a multi-criteria method in order to offer more purposeful perspectives on the association between ICT and CO_2, as shown in the current research using the QQR and Granger causality in quantiles techniques. Future research could potentially extend the connection to other elements impacting the debate over ICT and its influence on CO_2 emissions, including structural change, eco-innovation, and globalization.

Ethical approval

This research complies with internationally accepted standards for research practice and reporting.

Declarations

Author contribution statement

Tomiwa Sunday Adebayo: Conceived and designed the experiments; Performed the experiments; Analyzed and interpreted the data; Contributed reagents, materials, analysis tools or data; Wrote the paper.

Ephraim Bonah Agyekum, Hossam M. Zawbaa and Salah Kamel: Analyzed and interpreted the data; Wrote the paper.

Mehmet Altuntaş and Sadriddin Khudoyqulov: Performed the experiments; Contributed reagents, materials, analysis tools or data; Wrote the paper.

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Data will be made available on request.

Declaration of interests statement

The authors declare no conflict of interest.

Additional information

No additional information is available for this paper.

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