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ICT, Energy Intensity, and CO_2 Emission Nexus

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Abstract: The relationship between information and communication technology investment (ICT), environmental impacts, and economic growth has received increasing attention in the last 20 years. However, the relationship between ICT, energy intensity, environmental impacts, and economic growth was relatively neglected. In this paper, we aimed to contribute to the environmental literature by simultaneously analyzing the relationship between ICT, energy intensity, economic growth, Carbon dioxide (CO_2) emissions, and energy consumption for the period of 1990–2020 in G7 countries. We employed the Panel Quantile Auto Regressive Distributed Lag (PQARDL) method and Panel Quantile Granger Causality (PQGC) methods. According to the results of PQARDL method, energy consumption, ICT, CO_2 emission, and energy intensity have effects on economic growth in the long and short run. According to the of PQGC methods allowing causality results for different quantiles, there is evidence of a bidirectional causality between ICT investment and economic growth for all quantiles and evidence of a unidirectional causality from ICT to energy consumption and from CO_2 emissions to ICT investment and energy efficiency. Our results indicate that the governments of the G7 countries have placed energy efficiency and ICT investment at the center of their policies while determining their environmental and energy policies, since energy consumption is a continuous process.

Keywords: information and communication technologies (ICT) investment; energy intensity; economic growth; CO_2 emissions and energy consumption; Panel Quantile Auto Regressive Distributed Lag method; Panel Quantile Granger Causality methods

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1. Introduction

Information and communication technologies (ICT) investment have had a remarkable influence on economic, social, and cultural life recently. Information and communication technology with the wide-spread usage of internet, computers, and mobile phones has been growing rapidly for past 20 years [1,2]. Over the last two decades, there has been a huge advancement in ICT, enabling dramatic spread of internet and mobile technology [3]. In the 1980s, it was accepted that the economies changed towards more intensive use of information technology. During the 1990s, the adoption of ICTs increased rapidly.

The utilization of ICTs naturally has given rise to an increase in energy demand. According to a report published by [4], if the IT sector, especially data centers, were a country, it would be the fifth largest electricity consumer in the world. In spite of the fact that ICT usage raises electricity consumption at the micro level, it increases energy intensity by increasing the productivity [5].

The usage of ICT is defined as the "diverse set of technological tools and resources used to communicate and to create, disseminate, store, and manage information" by [6]. Manochehri et al. [7] claim that firms should establish necessary infrastructure and hire skilled ICT labor to benefit from ICT adoption. The business environment changes fast and this leads to increased reliance on ICTs to acquire methods and competitiveness, increase profit, and remain powerful in today's dynamic market [8]. This has been a primary source of adopting innovative activities, which are technology-based [9].

The analysis of the relationship between information technology and energy consumption goes back to 1950s with Thirring [6], but this relationship drew little attention until the 1980s. After the oil shocks in 1974 and 1979, some papers investigated the way of reducing energy consumption via information technology. After the pioneering papers of [10,11], some papers in pursuit of these papers investigated the relationship between ICT and economic growth, and some other papers tested the relationship between information technology and energy consumption. Then, some studies analyzed the relationship between energy consumption, CO_2 emissions, and information technology.

Nowadays, CO_2 emissions caused by human activity have become a serious threat worldwide and have risen to an irreversible level. The dramatic increase in consumption of fossil fuel energy led to this serious level of CO_2 emissions [12]. According to International Energy Agency (2019), worldwide CO_2 emissions increased by 33.1 billion tons in 2018 due to the impact of fossil fuel energy consumption. In GEO-4 (4. Global Environment Outlook: UN, 2007) and GEO-6 (6. Global Environment Outlook: UN, 2019), industrial activities were cited guilty of GHG emissions, which increased the worldwide temperature by 0.74% [13].

The Intergovernmental Panel on Climate Change (IPCC)'s special report on renewable energy and climate change mitigation showed that the use of renewable energy is increasing globally. CO_2 emissions are therefore a very important problem. International Monetary Fund (IMF) pointed out that due to the impact of COVID-19, the global economy would experience a recession in 2020, and the economic growth rate would drop to −3% [14,15].

The monthly average CO_2 concentrations (i.e., 414.50 ppm in March 2020 against 411.97 ppm in March 2019) recorded by National Oceanic and Atmospheric Administration (NOAA), on the other hand, reveal that global atmospheric CO_2 concentrations have not yet dropped. It is a fact that there has been a decline in fossil fuel/carbon burning in various areas of the world, including urban and industrial zones, due to COVID-19, but there is no evident change in CO_2 emissions [16]. As CO_2 levels are influenced by the variability of plant-soil carbon cycles, as well as the nature of the carbon budget, atmospheric CO_2 concentrations are expected to rise unless annual emissions are reduced to zero [16–18]. Researchers predicted a drop equivalent to 5.5 percent of 2019's global total emissions for 2020 [19], while a more comprehensive assessment, taking COVID-19 forced confinement into account, projected an annual CO_2 emission reduction of 4 percent if pre-pandemic conditions returned by mid-June 2020, or up to 7 percent if some worldwide restrictions remained in place until the end of 2020 [18]. Nevertheless, global CO_2 emissions must be reduced by 7.6 percent per year [19,20] in order to avoid exceeding the 1.5 °C global temperature increase beyond pre-industrial levels, which is the threshold indicating a temperature limit within which the most catastrophic climatic dangers are present [21].

To our knowledge, these studies did not simultaneously analyze the relationship between energy intensity, energy consumption and ICT, economic growth and CO_2 emissions. This paper aims to contribute to the energy and environmental literature by simultaneously analyzing the relationship between ICT investment, energy intensity, economic growth, CO_2 emissions, and energy consumption by employing Panel Quantile Auto Regressive Distributed Lag (PQARDL) and Panel Quantile Granger Causality (PQGC) methods for the period of 1990–2020 in G7 countries. This paper contributes to the related literature on theory and application points. By referring [22,23], we used PQARDL method. For panel data, the PQARDL model allows for the testing of the long-run relationship with the related short-run movements for quantiles. In pursuit of these papers, the PQARDL method will apply and the PQGC method will apply [24]. So, for panel data, the PQARDL model will allow for the testing of the long-run and short-run results for quantiles. The PQGC method will determine the direction of causality for quantiles that is robust to outliers and heavy distributions. These methods will offer some improvements to solve the econometric model due to quantile methods. Firstly, contrary to the panel models, the

PQARDL method offers a more comprehensive picture of the short- and long-run results. Secondly, the PQARDL method has some advantages over the panel ARDL method. It is robust to outliers and heavy distributions. More robust results can be obtained from PQRDL. Thirdly, when the variables are analyzed as a whole with traditional methods without considering the quantiles, traditional cointegration methods can cause spurious estimations whereas quantile methods do not. Fourth, moreover, the ecm coefficients determined by the PQARDL method provide information for each quantile unlike other tests. This technique can obtain the estimated coefficients across the different quantiles. Lastly, by depending on the Granger causality results obtained for different quantiles, this paper will offer important implications for ICT policies, energy policies, and growth policies in G7 countries.

This paper will contribute to the related literature on theory and application points. Concerning environmental literature, it will contribute to the theory by determining the contribution of the selected variables on a sustainable environment. Concerning application points, to our knowledge, this paper is the first paper that simultaneously applies the PQARDL and PQGC methods to analyze the relation between energy intensity, energy consumption and ICT, economic growth, and CO_2 emissions. The employment of the PQARDL method and PQGC methods will provide important implications for ICT policies, energy policies, and growth policies in G7 countries as mentioned above.

The literature review is given in the next section. The econometric methodology and model utilized in this study are provided in section three. Section four will address the empirical results, and the last section will provide a discussion of the findings together with policy implications.

2. The Literature Review

As mentioned above, the analysis of the relationship between information technology and energy consumption goes back to 1950s with [10], but this relationship drew little attention until the 1980s (e.g., Walker, 1985, 1986). There are lots of works examining the effect of ICT (especially telecommunications infrastructure and tele density) on economic growth recently. The studies conducted by [25,26] were the earliest attempts to use causality tests to investigate the causal relationship between economic growth and telecommunications development. Madden and Savage [27], Cronin, et al. [25], Cronin, et al. [26], Dutta [28], Chakraborty and Nandi [29] have confirmed the existence of a unidirectional causality from ICT to economic growth, but Shinjo and Zhang [30] found a unidirectional causality from economic growth to ICT investment. Pradhan et.al. [31] tested the relationship between the development of telecommunications infrastructure (DTI) and economic growth in G-20 countries over the period 1991–2012 via panel vector auto-regressive model and Granger causality. They determined a bidirectional causality between DTI and economic growth. In this perspective, refs. [25,26] determined a bidirectional causality between telecommunications infrastructure and economic growth in the United States of America (USA).

Some papers analyzed the relationship between ICT and energy consumption. Cho et al. [32] tested the relationship between ICT and electricity consumption in South Korea from 1991 to 2003. Røpke et al. [33] tested the effect of ICT on household electricity consumption in Denmark. According to the results, the integration of ICT development increases electricity consumption. Ishida [34] revealed the presence of a long-run relationship between the functions of energy demand and production. It is concluded that, while ICT reduces energy consumption moderately, it does not lead to an increase in GDP. Salahudin and Alam [5] analyzed the relationship between economic growth, internet use, and electricity consumption by using the ARDL bounds test and Granger causality test for Australia over the period 1985–2012. They determined a unidirectional causal relationship between internet usage and electricity consumption and economic growth. Awad [35] found ICT have no apparent effect on environmental quality. Bastida et al. [36] found that household electricity consumption can be reduced by ICT-based effects on consumer behavior. Some papers focused on the relationship between ICT investment and energy efficiency. Panajotovic et al. [37] linked ICT to the overall efficiency of energy use. Laitner [38] accented that ICT escalates both economic growth and the efficiencies of energy use. Laitner [38] found evidence for 13 Organization of Economic Cooperation and Development (OECD) countries where ICT led to a higher energy efficiency by decreasing the electricity demand.

Some papers analyzed the relationship between the consumption of ICT goods and services' energy consumption and CO_2 emissions. Moyer and Hughes [39] and Avom et al. [40] found that ICT can directly aggravate the CO_2 emissions. In [41], 16 EU countries over the 1990–2017 period were analyzed. The results showed that there is a unidirectional causality from electricity consumption and ICT usage to CO_2 emissions and improved GDP. ICT and power use increase, causing CO_2 emissions to grow and Gross Domestic Product (GDP) to rise. In [42] it was found that, for G7 countries from 1990 to 2014, ICT had a positive long-term effect on CO_2 emissions. Nevertheless, their interaction reveals a mixture of impacts on economic growth, both negative in the long term and positive in the short term. In [43] it was found that, for 16 EU countries from 1990–2017, ICT and power use increase caused CO_2 emissions to grow and GDP to rise. Miśkiewicz et al. [44] analyzed climate change, innovation and information technology, and CO_2 emissions for Visegrád countries (Hungary, Poland, Check Republic, and Slovakia) from 2007–2016 and found the development of information and innovation technologies had a statistically significant effect on CO_2 emissions. Furthermore, according to [40], despite the consumption of ICT goods and services being argued to directly aggravate the CO_2 emissions into the atmosphere, the impacts can indirectly be reversed through the ICT-enabled enhancement of energy use efficiencies and greening of the ICT sector. Bastida et al. [36] found ICT-based effects on consumer behavior can reduce household final electricity consumption by 0–5%. These and other findings from the literature are used to define parameter values, which reflect the efficacy of ICT at changing household energy usage patterns, and ultimately decreasing GHG emissions from the electricity sector.

Some papers focused on the relationship between ICT–RE consumption [37] have also linked ICT to the overall efficiency of energy use. Laitner [38] accented that ICT escalates both economic and efficiencies of energy use. Moyer and Hughes [36], Khan et al. [45], Park et al. [46], Raheem et al. [42], and Avom et al. [40] found that ICT can directly aggravate CO_2 emissions. Murshed [47] analyzed the non-linear impacts of ICT trade for some South Asian economies: The results reveal that ICT trade increases renewable energy consumption, reduces the intensity of energy use, and reduces carbon-dioxide emissions. Danish et al. [48] found that ICT decreases the level of CO_2 released in high-and middle-income countries, but ICT increases CO_2 released in low-income countries. Asongu et al. [49] studied the impact of ICT on CO_2 by a generalized method of moment method. According to their results, growing ICT decreases CO_2 release. Adha et al. [50] analyzed 20 cities in Taiwan and found a bidirectional causality between ICT and electricity demand, climate change indirectly affects the use of electricity through household appliances. Zhu et al. [51] analyzed the relationship between energy consumption and environmental pollution.

Table 1 shows some results about the relationship between ICT, renewable energy, economic growth, CO_2 emissions, and energy consumption for 2020 and 2021.

Table 1. The literatures between ICT, renewable energy, economic growth, CO_2 emissions, and energy consumption.

Author(s)	Countries	Data Period	Methodology	Variables	Finding(s)
Raheem et al. [42]	G7 countries	1990–2014	PMG	ICT, financial development, GDP, CO_2 emissions	FD is a weak determinant while ICT has a positive long-term impact on emissions. ICT and FD variables were found to have a negative effect on economic growth. Nevertheless, their interaction reveals a mixture of impacts on economic growth, both positive in the short term and negative in the long term.

Table 1. *Cont.*

Author(s)	Countries	Data Period	Methodology	Variables	Finding(s)
Arshad et al. [43]	South and Southeast Asian (SSEA) region	1990–2014	Kuznets curve (EKC) hypothesis	ICT, financial development, energy consumption, trade, economic growth, CO_2 emissions	ICT and financial development degraded the environmental quality of the SSEA region, implying that ICT products and services are not efficient in terms of energy in both potential countries and developed countries, and the majority of financial investments are located in unfriendly environmental projects in potential countries.
Magazzino et al. [41]	16 EU countries	1990–2017	Dumitrescu-Hurlin panel causality test	ICT penetration, electricity consumption, economic growth, urbanization, and environmental pollution	ICT and power use increase, causing CO_2 emissions to grow and GDP to rise.
Miśkiewicz [44]	Visegrád countries (Hungary, Poland, Check Republic, Slovakia)	2000–2019	OLS, fully modified OLS (FMOLS), dynamic OLS (DMOLS)	Climate change, innovation and information technology, greenhouse gas (GHG) emission	The development of information and innovation technologies has a statistically significant effect on GHG emissions.
Khan et al. [45]	Canada	1989–2020	Time series model (Dynamic ARDL simulations)	Financial development, environmental-related technologies, research and development, energy intensity, renewable energy production, natural resource depletion, sustainability	Environmental technologies in Canada assist to decrease environmental degradation in both the short and long term. Simultaneously, financial development, energy intensity, renewable energy generation, research and development, natural resource depletion, and temperature factors contribute to Canada's environmental deterioration.
Adebayo and Kirikkaleli [52]	Japan	1990–2015	Wavelet transformation	Renewable energy consumption, CO_2 emissions, economic growth, technological innovation, globalization	Globalization, growth of GDP development, and technological innovation all contribute to increased CO_2 emissions in Japan, whereas renewable energy use reduces CO_2 emissions in the short and medium term.

3. Data and Methodology

3.1. Data

In this study, annual data were used that cover the period of 1990–2020. CO_2 emissions, economic growth (Real GDP in constant 2005 USD), information and communication technologies (ICT investment), energy consumption, and energy intensity are used. Table 2 defines the variables. Data were taken from World Bank [40]. We used logarithmic transformation for all variables.

Table 3 presents descriptive statistics. ICT and Y variables have negative skewness whereas others have positive.

3.2. Methodology

Methodology was given two sub-titles, PQARDL and PQGC.

Table 2. Variables.

	Variables	Data Sources	Metrics
ict	Information and communication technologies	World Bank	Individuals using the Internet
y	Economic growth	World Bank	Real GDP in constant 2005 USD
ec	Energy consumption	World Bank	kg of oil equivalent
co	CO_2 emissions	World Bank	metric tons
c	Energy efficiency	World Bank	MJ$2011 PPP GDP

Table 3. Descriptive Statistics.

	Variables	Descriptive Statistics			
		Max	**Std. Dev.**	**Kurtosis**	**Skewness**
co	CO_2 emissions	1.311	0.180	2.020	0.194
y	Economic growth	3.868	1.336	2.585	−0.645
ict	ICT	1.98	0.929	2.071	−0.479
c	Energy consumption	3.927	0.160	1.994	0.546
ec	Energy intensity	1.024	0.143	2.486	0.509

3.2.1. PQARDL Method

Unlike panel models, the PQARDL technique provides a more complete picture of short- and long-term outcomes. Outliers and heavy distributions are not a problem in this technique. Compared to the panel ARDL approach, the PQARDL method has a few advantages. PQRDL can produce more reliable results. Koenker and Bassett [53] proposed panel quantile regression (PQR), which has several advantages over OLS regression. The PQR results are more reliable than other one [54]. It is also necessary to use PQR to shape distributional assumptions [55]. Furthermore, the properties of the whole conditional distribution of the selected variables can be captured using this technique [56,57]. To this end, quantile regression was proposed by [53] to investigate asymmetric aspects of variable distributions [57]. Refs. [22–24,51,58] applied PQARDL technique

The conditional quantile of y_i is

$$Q_{yi}(\tau|x_i) = x_i^T \beta_\tau \quad (1)$$

PQR is robust to heavy distributions and outliers [22–24,51].

The Panel Quantile Autoregressive Distributed Lags method is developed as follows:

$$Q_{yi}(\tau_k|\alpha_i, x_{it}) = \alpha_i(\tau_k) + \sum_{j=1}^{p} \alpha_j(\tau_k) y_{it-j} + \sum_{m=0}^{q} \beta_m(\tau_k) x_{it-m}^T, i = 1, \ldots, N; t = 1, \ldots, T \quad (2)$$

and t is the index of time. The parameter estimate is calculated as follows

$$Y_{it} = \alpha_i(\tau_k) + \sum_{j=1}^{p} \alpha_j(\tau_k) y_{it-j} + \sum_{m=0}^{q} \beta_m(\tau_k) x_{it-m}^T + \varepsilon_{it}(\tau_k) \; i = 1, \ldots, N; t = 1, \ldots, T \quad (3)$$

Equation (3) is accepted as the panel quantile autoregressive distributed lag (PQARDL).
$\varepsilon_{it}(\tau_k)$ is donated as $Y_i - Q_{yi}(\tau_k|\alpha_i, x_{it})$ and rewritten as follows

$$Y_{it} = \alpha_i(\tau_k) + \sum_{j=0}^{q-1} W_{it-j}\delta_{it,j}(\tau_k) + X'_{it}\gamma_0(\tau_k) + \sum_{m=0}^{p} \theta_{it,m}(\tau_k)Y_{it-m} + \varepsilon_{it}(\tau_k) \;\; i = 1,\ldots,N; t = 1,\ldots,T$$
$$\text{where } \gamma_0(\tau_k) := \sum_{j=0}^{p}\theta_{it,m}(\tau_k), W_{it} := \Delta X_{it} \text{ and } \delta_{it,j}(\tau_k) := -\sum_{i=j+1}^{p}\theta_{it,m}(\tau_k). \text{ For given } \tau \in (0,1) \tag{4}$$

Dynamics are obtained by solving the minimization problem:

$$\min_{(\alpha,\beta)} \sum_{k=1}^{K}\sum_{t=1}^{T}\sum_{n=1}^{N} w_k\rho_{\tau k}(y_{it} - \alpha_i - \sum_{j=0}^{p} W'_{it}\delta_{it,j}(\tau_k) + \sum_{i=j+1}^{p} \phi_{it,m}Y_{t-j}). \tag{5}$$

The PQARDL process is used as follows:

$$Q_{yi}(\tau_k|.) = \alpha_i(\tau_k) + \varsigma(\tau_k)(Y_{it-1} - X'_{it-1}\beta(\tau)) + \sum_{j=1}^{p-1}\phi_j(\tau_k)y_{it-j} + \sum_{m=0}^{q-1}\lambda_m(\tau_k)\Delta x^T_{it-m}, i = 1,\ldots,N; t = 1,\ldots,T$$
$$\text{where } \varsigma(\tau_k) = \sum_{j=1}^{p}\phi_j(\tau_k) - 1, \lambda_0(\tau_k) = \gamma(\tau_k) + \delta_0(\tau_k), \phi_j(\tau_k) = -\sum_{i=j+1}^{p}\phi_i(\tau_k) \text{ and } \lambda_j(\tau_k) = -\sum_{i=j+1}^{p}\delta_i(\tau_k) \tag{6}$$

3.2.2. Panel Quantile Granger Causality (PQGC) Method

Troster et al. [59] developed the procedure for time series. Their method for Granger-causality in quantiles does not require the smoothing parameters to be determined. The test contains testing the null hypothesis of non-causality between two variables, say from Z_t to Y_t:

$$H_0^{Z\nrightarrow Y} : F_Y\left(y|I^Y_{i,t}, I^Z_{i,t}\right) = F_Y\left(y|I^Y_{i,t}\right) \text{ for all y} \in \mathbb{R} \tag{7}$$

$I_{i,t}\left(I^{Y\prime}_{i,t}, I^{Z\prime}_{i,t}\right) \in \mathbb{R}^d$ $d = s + q$, and $I^Y_{i,t} = (Y_{i,t-1},\ldots,Y_{i,t-s})' \in \mathbb{R}^s$ *and* $I^Z_{i,t} = (Z_{i,t-1},\ldots,Z_{i,t-q})'$ $\in \mathbb{R}^q$. The test for Granger (non)-causation from Z_t and Y_t in distribution—that is, across τ-quantiles—for Equation (7) is:

$$H_0^{QC\ Z\nrightarrow Y} : Q^{Y,Z}_\tau\left(Y_{i,t}|I^Y_{i,t}, I^Z_{i,t}\right) = Q^Y_\tau\left(Y_{i,t}|I^Y_{i,t}\right) \text{ for all } \tau \in \tau \tag{8}$$

where the τ-quantiles of $F_y = (.|I^Y_{it}, I^Z_{it})$ *and* $F_y = (.|I^Y_{it})$ are represented by $Q^{Y,Z}_\tau(.|I^Y_{i,t})$ *and* $Q^{Y,Z}_\tau = (.|I^Y_{i,t})$, respectively. In addition, $\tau \subset (0,1)$ is a compact set and the following restrictions satisfied by Y'_{it}'s conditional τ-quantiles is defined

$$P\left\{Y_{i,t} \le Q^Y_\tau\left(Y_{i,t}|I^Y_{i,t}\right)\middle|I^Y_{i,t}\right\} := \tau, \text{ for all } \tau \in \tau$$
$$P\left\{Y_{i,t} \le Q^{Y,Z}_\tau\left(Y_{i,t}|I^Y_{i,t}, I^Z_{i,t}\right)\middle|I^Y_{i,t}, I^Z_{i,t}\right\} := \tau, \text{ for all } \tau \in \tau \tag{9}$$

And $E\{Y_{i,t} \le Q_\tau(Y_{i,t}|I_{i,t})|I_{i,t}\} = E\left\{1\left[Y_{i,t} \le Q_\tau(Y_{i,t}|I_{i,t})\middle|I_{i,t}\right]\right\}$ the null hypothesis of Granger non-causality is rewritten as

$$H_0^{Z\nrightarrow Y} : E\{1[Y_t \le m(I^Y_t, \theta_0(\tau))]|I^Y_t, I^Z_t\}\tau$$
$$H_0^{Z\nrightarrow Y} : E\{1[Y_t \le m(I^Y_t, \theta_0(\tau))]|I^Y_t, I^Z_t\} \neq \tau \tag{10}$$

And $m(I^Y_t, \theta_0(\tau))$ spesifies $Q^Y_\tau(.|I^Y_t)$.

The test statistic for the direction of the Granger-causality is as follows:

$$S_{iT} = \frac{1}{Ti, n}\sum_{j=1}^{n}\left|\Psi'_{.ij}W_{\Psi.ij}\right| \tag{11}$$

where n denotes the equidistributed points over the grid

$\tau_{i,n} = \{\tau_{ij}\}_{j=1}^{n}$
W is a $T \times T$ matrix.
$w_{t,s} = \exp\left[-0.5(I_t - I_s)^2\right]$, Ψ is $T \times n$, matrix with elements and

$$\Psi_{i,j} = \Psi_{\tau j}(Y_i^{\Upsilon} - m(I_i^{\Upsilon}, Q_{\tau}(\tau_j)). \tag{12}$$

4. Results

To explore cross-sectional dependence, the results were given in Table 4. Four different tests were applied. If the results of all all tests point to same inference, results will be accepted as true. According to test results, the decision about using the first-generation or second-generation unit rot tests will be made.

Table 4. Cross-sectional dependence tests.

Variables	Breusch-Pagan LM	Pesaran Scaled LM	Bias-Corrected Scaled LM Test	Pesaran CD
y	263.93	36.40	36.38	14.07
c	316.44	44.50	44.49	17.08
ce	471.08	68.36	68.32	21.29
ict	634.91	93.64	93.63	25.19
co	262.80	36.23	36.21	13.57

Table 4 shows that at the 1% level, the tests provide rejection of the null hypothesis of no cross-sectional dependence. To avoid inconsistency, LLC, ADF Fisher X^2, PP Fisher X^2, and CIPS tests were applied.

Table 5 shows the findings determined by the LLC, ADF Fisher X^2, PP Fisher X^2, and CIPS tests. For the variables, it was determined the evidence of I (1). Before applying PQARDL, we made PARDL tests in order to determine the dependent variable. After determining the dependent variable, we set up the PQARDL model. According to the results in Table 6, y is determined as dependent variable.

Table 5. LLC and CIPS Results.

	Level				First Difference				Decision
	LLC	CIPS	ADF Fisher X^2 Square	PP Fisher X^2 Chi-Square	LLC	CIPS	ADF Fisher X^2 Square	PP Fisher X^2 Chi-Square	
co	1.59	1.85	6.81	10.16	−12.36	−17.81	194.51	192.98	I(1)
ec	3.59	5.39	2.91	4.08	−3.84	−6.13	66.58	130.41	I(1)
c	3.59	3.85	4.81	8.16	−3.09	−5.06	51.94	137.78	I(1)
y	−1.03	−2.49	9.81	11.39	−4.80	−9.09	98.90	144.13	I(1)
ict	−1.58	0.01	10.24	18.61	−7.47	−6.75	71.57	168.04	I(1)

Table 6. The Results of the Panel ARDL Bounds Testing Cointegration Tests.

Dependent/Independent Variable	Statistic	Cointegration Result	Ramsey's Reset Test	Breusch-Godfrey Test	Jarque-Bera Test
(lco/ly, lec, lc, lict)	2.07	No-Cointegration			
(lc/lco, lec, ly, lict)	1.17	No-Cointegration			
(ly/lco, lec, lc, lict)	14.81	Cointegration	0.27 (0.59)	1.59 (0.21)	2.58 (0.27)
(lec/ly, lec, lco, lict)	2.33	No-Cointegration			
(lict/ly, lec, lc, lco)	1.88	No-Cointegration			

Table 6 shows the estimated F statistic and that the values are all above the upper critical bounds. When economic growth is accepted as the dependent variable, our model gives successful results. After this stage, we can proceed with short-run and long-run estimations. In Tables 7 and 8, both PARDL and PQARDL results are presented to compare the results and to show the consistency.

Table 7. Long-run Results.

	PARDL	PQARDL				
		0.1th	***0.25th***	***0.5th***	***0.75th***	***0.95th***
lict	0.106 (2.21)	0.923 (2.66)	0.949 (2.97)	0.718 (2.04)	0.678 (2.04)	1.37 (2.15)
lco	−1.963 (1.09)	1.832 (4.47)	2.1814 (4.21)	1.230 (3.15)	1.861 (2.92)	1.264 (2.50)
lc	−0.877 (2.89)	1.01 (2.18)	0.1825 (2.03)	0.238 (2.05)	−0.275 (−1.93)	−0.905 (−2.33)
lec	1.249 (1.58)	1.008 (4.10)	2.087 (2.57)	1.522 (2.33)	1.046 (2.38)	1.210 (3.40)

Table 8. Short-run PQARDL and PARDL Results.

Dependent Variable: Y						
			PQARDL		**PARDL**	
	0.1th	**0.25th**	**0.5th**	**0.75th**	**0.95th**	
Δlc	1.825 (4.21)	1.135 (2.11)	1.205 (3.12)	0.5809 (2.86)	1.2564 (3.19)	1.83 (2.15)
Δlec	1.77 (8.20)	1.081 (4.50)	1.156 (3.99)	1.0733 (2.66)	0.3141 (3.64)	−1.71 (3.18)
Δlict	0.684 (2.54)	0.705 (2.77)	0.663 (2.02)	0.7742 (1.93)	1.0787 (1.92)	−1.91 (2.53)
Δlco	−1.26 (−5.31)	−1.96 (−2.29)	−0.46 (−0.09)	1.4533 (2.35)	1.0557 (3.54)	1.58 (1.99)
ecm	−0.26 (2.13)	−0.45 (1.96)	−0.37 (1.89)	−0.33 (2.07)	−0.39 (2.11)	−0.56 (1.86)

4.1. Long-Run Coefficients

In Tables 7 and 8, according to the results, all variables have statistically significant impacts on economic growth. In addition, the tables provide results between the PARDL and PQARDL models. Comparison between models gives the superiority of the applied model over the PARDL model.

The coefficients of energy consumption (c) are positive except the 75th and 95th quantiles. The results for 0.75th and 0.95th quantiles have negative coefficients and these results are similar to PARDL. The coefficients of CO_2 emission are positive in all quantiles of the PQARDL model but negative in the PARDL model. The coefficients of energy intensity (ec) and information and communication technologies (ict) are positive in all quantiles. They have a positive impact on economic growth on the long run. lec and lco variables are statistically insignificant in the PARDL model. Coefficients can be evaluated as elasticities; energy consumption and ICT elasticities of economic growth are smaller than 1 in more cases, except for the 0.95 quantiles for ict and the 0.75 and 0.95 quantiles for c, which have negative coefficients. Energy intensity and CO_2 emission elasticities of growth are greater than 1 in all cases.

4.2. Short-Run Coefficients

The coefficients of energy consumption (c) differ according to quantiles. The coefficients of CO_2 emission (co) are negative until 0.75th quantile, then they become positive for other quantiles. The coefficients of energy intensity (ec) and information and communication technologies (ict) are positive in all quantiles but negative in the PARDL model.

We found that energy consumption, energy intensity, CO_2 emissions, and information and communication technologies have statistically significant effects on economic growth in the short run. All coefficients of ECM are statistically significant and negative as expected. They range between −0.26 and −0.45. In the PARDL model, the ECM coefficient has a high value at −0.56. This indicates a relatively rapid adjustment to the long-term equilibrium. In PQARDL, the ECM coefficient at the 0.1 quantile is relatively low at −0.26. In this model, the highest ECM coefficient is obtained at the 0.25 quantile, which has a value of −0.45. The ECM coefficients obtained by the PQARDL method are lower in value than those obtained by PARDL.

4.3. Causality

In Table 9, the results indicate that there is a unidirectional causality from information communication technologies to energy consumption (except at the 0.25th quantile bidirectional causality), from information communication technologies to economic growth (except at the 0.75th quantile bidirectional causality), and from information communication technologies to energy efficiency. There is also a unidirectional causality from energy consumption to CO_2 emissions for the 0.10th, 0.50th, and 0.95th quantiles, a bidirectional causality for the 0.25th quantile, and none causality for the 0.75th quantile. It was found the evidence of unidirectional causality from energy consumption to economic growth for all quantiles. The evidence of a unidirectional causality from energy consumption to economic growth corrects the growth hypothesis for all quantiles. There is also a unidirectional causality from CO_2 emissions to economic growth (except bidirectional causality for the 0.95th quantile) for all quantiles. There is evidence of a bidirectional causality between energy efficiency and economic growth for all quantiles.

Table 9. Causality results.

	0.1	**0.25**	**0.5**	**0.75**	**0.95**
Δlco→Δlc	0.45	2.77	0.453	1.37	0.51
Δlc→Δlco	2.55	2.62	2.571	1.78	2.90
Direction of causality	C→CO	⟷	C→CO	None	C→CO
Δlec→Δlc	7.11	3.65	7.11	2.38	2.74
Δlc→Δlec	1.18	8.99	11.8	2.02	6.90
Direction of causality	EC→C	⟷	⟷	⟷	⟷
Δly→Δlc	0.74	0.49	0.748	0.19	0.49
Δlc→Δly	9.60	5.21	9.60	5.41	2.89
Direction of causality	C→Y	C→Y	C→Y	C→Y	C→Y
Δlict→Δlc	9.04	5.05	9.04	15.54	3.25
Δlc→Δlict	0.33	5.83	0.244	0.33	0.92
Direction of causality	ICT→C	⟷	ICT→C	ICT→C	ICT→C
Δlec→Δlco	0.96	0.87	0.96	0.24	0.55
Δlco→Δlec	8.82	4.76	8.82	11.85	3.71
Direction of causality	CO→EC	CO→EC	CO→EC	CO→EC	CO→EC
Δly→Δlco	0.11	0.40	0.11	0.05	3.97
Δlco→Δly	8.49	4.55	8.49	3.65	2.82
Direction of causality	CO→Y	CO→Y	CO→Y	CO→Y	⟷
Δlict→Δlco	0.69	0.16	1.69	1.56	0.21
Δlco→Δlict	4.79	2.20	5.17	4.346	3.43
Direction of causality	CO→ICT	CO→ICT	CO→ICT	CO→ICT	CO→ICT
Δly→Δlec	7.27	5.84	7.27	8.56	5.31
Δlec→Δly	6.98	9.07	2.89	2.70	5.96
Direction of causality	⟷	⟷	⟷	⟷	⟷
Δlict→Δlec	4.52	2.71	4.52	3.65	3.78
Δlec→Δlict	0.50	0.45	1.12	0.30	0.98
Direction of causality	ICT→EC	ICT→EC	ICT→EC	ICT→EC	ICT→EC
Δlict→Δly	2.54	2.85	2.54	2.41	2.63
Δly→Δlict	1.06	0.58	1.06	3.43	1.68
Direction of causality	ICT→Y	ICT→Y	ICT→Y	⟷	ICT→Y

In the literature, economic growth is the Granger cause of environmental degradation, which is defined in Environmental Kuznets Curve Hypothesis, but in our results CO_2 emissions are the Granger cause of economic growth. G7 countries should increase energy efficiency to overcome environmental degradation according to our results, and we determined that ICT is an important factor for sustaining energy efficiency.

5. Discussion

This study utilizes the panel quantile method together with ARDL and Granger Causality methods and these methods allow for obtaining and comparing different results in the long- and short-run for all quantiles and direction of causality for all quantiles. In the PQARDL model, energy consumption, ICT investments, CO_2 emissions, and energy intensity have positive and statistically significant effects on economic growth in the long run. Energy consumption and ICT investments elasticities of economic growth are smaller than one in more cases, whereas energy intensity and CO_2 emission elasticities of growth are greater than one. ECM coefficients for all quantiles are statistically significant and negative as expected. The ECM coefficients change between -0.26 and -0.45 for different quantiles. We applied a PARDL model to compare the coefficients of variables and ECM. By the PARDL model, the ECM coefficient was found as -0.56. This is a very important difference in the context of economic policy proposals, because the long-term equilibrium adjustment is faster in the PARDL model than in the PQARDL model. The policies to be implemented in this context may differ.

According to our causality results, the evidence of a unidirectional causality from ICT to economic growth was determined (except at the 0.75th quantile) and in the 0.75 quantile, evidence of a bidirectional causality was found. In the 0.75 quantile, ICT is the Granger cause of economic growth and economic growth is the Granger cause of ICT. On the other hand, the evidence of a unidirectional causality from ICT to energy efficiency, and from ICT to energy consumption (except at the 0.25 quantile) were determined. Evidence of a unidirectional causality from CO_2 emissions to ICT was determined, and from CO_2 emissions to energy efficiency. CO_2 emissions are the Granger cause of ICT and energy efficiency. Except at the 0.25th and 0.75th quantiles, evidence determined a unidirectional causality from energy consumption to CO_2 emissions, and it was found a bidirectional causality for the 0.25th quantile and none causality for 0.75 quantile. Increasing ICT causes rising energy consumption, and energy consumption is the Granger cause of both GDP growth and CO_2 emissions (except at the 0.75th quantile). As an interesting result, CO_2 emissions are the Granger cause of economic growth. In the literature, economic growth is the Granger cause of environmental degradation, which is defined in Environmental Kuznets Curve Hypothesis. Similar to our results, Wang et al. [60] accented for 134 countries that the positive impact of economic growth on ecological footprint is higher than that of CO_2 releases.

According to our results, G7 countries should increase energy efficiency to overcome environmental degradation, and ICT is an important factor for sustainable energy efficiency. The governments have to design energy policies with expanding ICT investment in the context of its effects on economic growth. In the short-term, increasing ICT can cause rising energy consumption, and the increase in energy consumption initially increases environmental pollution. Similar to our results, refs. [2,5] showed that an increase in ICT will increase energy consumption. Additionally, ref. [49] showed that ICT investments are responsible for rising CO_2 emissions. In the context of ICT, large datacenters and mobile data traffic can be an enormous threat on the environment [61]. Moreover, both the processing and production of ICT appliances are responsible for rising CO_2 releases [49]. However, in long term, it creates positive effects on environmental pollution due to its positive effects on energy efficiency, and ICT will support consumers to use energy more efficiently through contributing to switching to a low-carbon energy mechanism. As another important effect in the long run, ICT leads to economic growth. It will provide more leisure time for employees and higher profits for companies because it increases productivity and efficiency.

The governments in G7 countries must determine the policies to provide efficient energy at home and in workplaces, businesses, etc. At home and at workplaces, businesses, etc., the use of environmentally friendly appliances that meet green appliance standards can be promoted, and efficient technologies in workplace, businesses, etc., can be adopted.

In G7 countries in the long-run, the transformation to e-books, e-paper, and email leads to the consumption of less energy [46]. Moreover, in these countries, online services decrease the necessity for a physical presence, and can decrease business travel. All these advancements can provide opportunities for saving energy consumption [48]. On the other hand, teleconferencing and teleworking can decline CO_2 release by decreasing energy consumption. Moreover, G7 countries have benefitted from technology spillover effects for the last 30 years. Traditional industry in these countries shifts to higher energy efficiency under the effect of the usage of ICT technologies. Our findings are consistent with other works (see for similar results; [46,48]).

The energy efficiency policies must be supported with energy conservation programs [50]. These programs are connected to the community's efforts to decrease their energy usage by embracing energy-saving behaviors. The governments in these countries must to coordinate ICT policies, environmental policies, energy policies, and economic growth policies.

As emphasized by some papers, positive effects on the environment can be increased by increasing renewable energy consumption. Renewable energy consumption has a positive impact on CO_2 release, moreover, it positively impacts economic development [61–63].

6. Conclusions and Discussion

In this paper, we analyzed the cointegration and causality between ICT, energy intensity, CO_2 emissions, energy consumption, and economic growth by employing the PQARDL and PQGC methods in G7 countries for the period of 1990–2020. According to the results of the PQGC method, there is a unidirectional causality from ICT to economic growth and for 0.75th quantile there is a bidirectional causality between economic growth and ICT. The evidence of a unidirectional causality from ICT to energy efficiency, and from ICT to energy consumption (except at the 0.25 quantile) were determined. As another result, it was found that CO_2 emissions are the Granger cause of ICT, economic growth, and energy efficiency. And except at the 0.75th quantiles, energy consumption is Granger cause of CO_2 emissions.

These results suggest policymakers should accelerate economic growth and promote ICT advancements to have more renewable energy output, which causes greater energy savings and a cleaner environment. Policymakers have to promote energy intensity and energy consumption policies (subsidize both consumption and production up to certain level) to accelerate economic growth and to support a sustainable environment. ICT application in economic activities can promote renewable energy consumption compared to nonrenewable energy consumption and helps to overcome limitations of renewable energy through facilitating the storage of renewable energy generation.

This study explores the causality relationships between ICT, energy intensity, CO_2 emissions, energy consumption, and economic growth empirically and can be a candidate for further academic research, especially for energy economics and innovation economics researchers. Results of this study can be used to analyze similar or different variables about these subjects in the future. This study can also shed light on economic policies, energy policies, and innovation policies through its conclusions.

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