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Impact of Information and Communication Technologies on Energy Consumption and Economic Growth: An Empirical Assessment for China

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Regarding the association between information and communication technology (ICT) and economic growth and energy consumption, particularly in developing economies, there is a great deal of controversy and a lack of empirical study. This study applies Quantile Autoregressive Distributed Lag Model (QARDL) approach to empirically probe into the effect of ICT on energy consumption and economic growth in China. Two corresponding models for energy consumption and economic growth are formulated and the data of all of the variables spanning over 1995–2021 period is taken from different secondary sources. The findings of the study reveal significant and positive impact of ICT on economic growth at all quantiles in the short and long run. Similarly ICT has significant and positive impact on energy consumption also at all quantiles. The Quantile Granger Causality test provides evidence for bidirectional causality between ICT and economic growth and ICT and energy consumption. Wald test proved the presence of and symmetric and linear association between ICT and economic growth and ICT and energy consumption at quantiles in the long and short run both. In the light of these findings, the study recommends the Chinese government and investors to have more investment in energy efficient ICT products that consume less energy and help increase in economic growth in China.

Keyword: *ICT; Energy Consumption; Economic Growth; QARDL; China.*

Introduction

Due to its broad acceptance over the past few decades, information and communication technology (ICT) has significantly transformed the world into an information society. In scale, scope and speed terms, businesses, governments and people now have significantly greater access to knowledge, wisdom and information than past, thanks to ICT infrastructure such as mobile phones, fixed-line telephones, the broadband and internet. ICT has greatly increased efficiency of resource allocation, dramatically reduced costs of production, and greatly increased investment and demand across all sectors of economy (Anggusti, 2022; Aslan & Batmaz, 2022; Bahrini & Qaffas, 2019; Damodharan & Ahmed, 2022). Key global systems including the energy and economic systems are affected by ICTs in a variety of ways (Draper & Schellenberg, 2022; Garvey *et al.*, 2021; Giaretta & Chesini, 2021; Moyer & Hughes, 2012). Numerous economic impacts of quick implementation and spread of these technologies include rising productivity, accelerating economic growth, and decreasing corruption. The world is consequently quickly transitioning from offline to online. Internet increases efficiency of markets, opens up economic opportunity, boosts production, and encourages political participation, according to the United Nations Development Program. The United Nations recognized that internet access is among fundamental human rights in modern society due to its growing importance in human activities (Bernardelli *et al.*, 2023; Guoqing & Lili, 2022; Hartani *et al.*, 2021; He, Leng, & Pan, 2022; Ilyas & Sampurno, 2022; Qin *et al.*, 2024; Radovic *et al.*, 2023; Salahuddin & Alam, 2016).

Many academics and scholars have concentrated on examining the effect of ICT on economic growth at production level, cross-country level and national level in light of the expanding significance of ICT and the ways in which it is reshaping the globe (Afzal & Gow, 2016; Bahrini & Qaffas, 2019; Kar, Bansal, & Mishra, 2021; Mamghaderi *et al.*, 2022; Mesic *et al.*, 2021; Octora *et al.*, 2022). Owing to its beneficial effects on employment and productivity, ICT is a major factor in the social and economic development of the nations, according to the majority of research in the field. Additionally, the World Bank, the OECD and the International Telecommunications Union (ITU), the World Bank, and other international institutions contend that ICT is a major force behind sustainable development. According to a World Economic Forum research, a country's GDP per person would improve by 0.75 percent and its unemployment rate would decrease by 1.02 percent if its digitalization increased by 10 percent. The OECD claims that ICT significantly contributes to the reduction of poverty by generating new income and employment sources, and by lowering the cost of access to educational and health services by poor people (Haller, 2023; Klimkiewicz *et al.*, 2023; Sahib *et al.*, 2022; Service, 2021; Sigurdsson *et al.*, 2021; Talha *et al.*, 2021; Toader *et al.*, 2018; Zhao *et al.*, 2024).

The quick development of ICT is essential for economic growth for a variety of reasons: this technology makes it possible for all parties involved in social and economic life to easily and quickly access knowledge and information (Sepehrdoust & Ghorbanseresht, 2019; Vildan & Kavak, 2021; Wahhab & Al-Shammari, 2021; Wray *et al.,* 2021; Yurtseven *et al.,* 2021; Zaman & Abd-el Moemen, 2017); ICT enables businesses to communicate more quickly and effectively, which lowers manufacturing costs and boosts efficiency (Meijers, 2014; Zhuo & Salleh, 2021); ICT also facilitates opening up new markets, reduces capital costs as a consequence of improved efficiency of financial market, reduces regional income disparities, and facilitates the availability of human capital via telenetworking (Pradhan, Mallik, & Bagchi, 2018); Because technology makes it easier to finance micro and small enterprises by lowering information asymmetry and agency costs, the ICT use, especially internet connectivity, can encourage the growth of micro and small firms and entrepreneurship (Chen *et al.,* 2018). ICT can effect economic growth significantly through a number of channels, including: the development of value-added services and products in an economy is directly influenced by the production of goods and services within the ICT sector; using ICT products and services as raw materials to create additional products and services; the ICT sector's rising productivity helps the economy as a whole increase its overall effectiveness; the application of ICT in different economic sectors (Allen *et al.,* 2022; Toader *et al.,* 2018).

There is also no question that the advancement and use of ICT have a significant effect on energy consumption. ICT, according to (Romm, 2002) can save energy use in two ways: 1- the development of the ICT sector results in less incremental energy consumption growth because its energy consumption is lower than that of traditional manufacturing industries. 2- By improving efficiency, ICT can decrease energy use across all economic sectors. However, because ICT equipment uses electricity, the advancement of these technologies can also result in an increase in energy use (Becker *et al.,* 2023). Consequently, the overall impact of the growth and spread of ICT remains a matter of empirical debate. Although the connection between ICT and energy consumption is particularly essential due to its environmental and economic implications, there are relatively few studies that look into this topic in the literature at the moment (Tunali, 2016).

There have been many theoretical and empirical studies done to address the following issue: how ICT impacts economic growth and energy consumption? There is increasing important of ICT in increasing economic growth, although empirical research on this nexus has produced conflicting results. While several empirical studies have shown that ICT diffusion significantly and favourably affects economic growth (Ahmed & Ridzuan, 2013; Bahrini & Qaffas, 2019; Fernandez-Portillo *et al.,* 2020; Toader *et al.,* 2018), negative relationship between ICT and economic growth was evident by (Garcia, 2019; Papaioannou & Dimelis, 2007; Pradhan *et al.,* 2018). Same conflicting views are also present for ICT and energy consumption (Collard *et al.,* 2005; Han *et al.,* 2016; Ishida, 2015; Laitner & Ehrhardt-Martinez, 2008).

The ambiguous conclusions regarding the nexus between economic growth, energy consumption, and ICT motivate us to dive again into the empirical estimation of this nexus particularly in the context of China. We selected China because China, which consumes the most energy and produces the most carbon dioxide emissions among industrialized and developing nations, has recently shown a constant exponential growth pattern. China presently consumes the second-largest amount of energy and the third-largest amount of coal globally. Since the start of the 2000s, China's energy consumption has increased by 8.8 % on average, which is nearly as much as the country's real GDP growth of 10.4 % for the same time period (Y. Wang, *et al.,* 2011). Additionally, China's economy is growing quickly and over the past 30 years has averaged an impressive 8 % rise in gross domestic product (GDP), mainly driven by increases in energy usage and resulting in carbon dioxide emissions. Growth in both energy use and CO2 emissions are inextricably linked to GDP growth (C.-C. Chang, 2010). With 33 % of the global CO2 emissions in 2020, China is the nation with the greatest emissions (11.9 billion tonnes) . Only China was responsible for 59 percent of CO2 emissions in Asia, so substantial action must be made by taking many options into consideration (Batool *et al.,* 2022).

Meanwhile, China is investing heavily in ICT, which helps to grow the economy of the country by generating income, creating jobs, and exporting commodities. China spent nearly twice as much on ICT infrastructure as it did on non-ICT infrastructure between 1978 and 2018, an increase of 21.8 % yearly. service sector of China utilizes ICT greater than its industrial sector (Tao Liang *et al.,* 2022). Through increased energy consumption, the ICT transition will benefit the ecological factor in addition to the economic aspects. According to Webb (2008), ICT services may have more positive environmental consequences than negative ones in terms of greenhouse gas emissions. 1.05 billion Individuals in China used the internet as of June 2022, or 74.4 percentage of the population. When China entered a time of an economic "New Normal," the government became interested in how ICT could hasten economic growth and change industrial processes. to incorporate ICT with energy system, the National Energy Administration supported 55 "Internet plus" smart energy demonstration projects in 2017 (Park *et al.,* 2018). In 1994, China installed its first web server, and by 1997, 620,000 people were using the internet there (Yu & Gao, 2023). After the year 2005, there was a significant rise in internet users. In 2013, just 39 % of Chinese households had access to broadband, but by 2021, the number of internet users was more than 1.02 billion, demonstrating the rapid growth of ICT in Chinese economy (Batool *et al.,* 2022). However, due to the necessity of electricity for the operation of ICT services and products, the country's rapid increase in ICT use is projected to have major energy consequences (Salahuddin & Alam, 2016; Sun & Choi, 2023).

The study is a novel contribution in the literature in the following aspects: first the number of empirical studies about the energy consumption, economic growth and ICT is quite limited with conflicting findings that necessitates further exploration. Thus the current study estimates the effect of ICT on economic growth and energy consumption. This study is the first such attempt to look at the consequences of ICT use on economic growth and energy consumption in a single study in China because no previous work has looked at this influence in a single framework.

Second, instead of using any single measure of digital economy like internet subscription, mobile phone subscription, number of individuals using internet, we developed a comprehensive index of digitalization incorporating all necessary representative components of ICT (see section 3 for details). And third, instead of studying linear relationship, the present study estimates the association over various quantiles by applying QARDL estimation approach. The long-term stability of the link across the quantiles can be examined using QARDL. It is superior to several other methods as described in more depth in the methodology section.

The remaining study is organized in the following order. Section 2 provides review of the previous literature. Section 3 includes data and empirical estimation technique. Section 4 provides empirical findings and their discussion. Section 5 provides conclusion and policy recommendations on the basis of the study findings.

Literature Review

We divide the existing literature into two strands: first strand covers economic growth and ICT nexus while second strand reviews energy consumption and ICT nexus.

ICT and Economic Growth

Many scholars and economists who have concentrated on examining the effect of ICT diffusion on the economic growth in developing and developed economies have become more and more aware of the ICT industry's rapid global advancement over the last three decades. Numerous empirical investigations into this relationship have yielded conflicting findings. For instance, (Bahrini & Qaffas, 2019) studied the effect of ICT on economic growth in Sub Saharan African countries and MENA by employing GMM estimation over 2007–2016 period. The authors concluded that except telephone subscriptions, all other measures of the ICT like mobile phone subscription, internet subscription and broadband subscription promoted economic growth in both regions. For EU countries (Toader *et al.,* 2018) estimated the role of ICT on economic growth over 2000 to 2017 period and according to the findings of the ICT had positive and significant impact on economic growth in the studied countries. (Aghaei & Rezagholizadeh, 2017) scrutinized the data for OIC countries by applying Fixed Effects and Random Effect model over 1990–2014 period. The study findings revealed the positive effect of ICT on economic growth in the selected countries. For India, (Erumban & Das, 2016) explored the role of ICT on economic growth and concluded that increasing ICT consumption was associated with increase in the economic growth in India. (Yousefi, 2011) scrutinized the data of 62 developing and developed countries over 2000 to 2006 period and authors found that in high income countries, ICT affected economic growth positively whereas in lower income countries ICT did not affect on economic growth significantly. For Indonesia (Rath & Hermawan, 2020) applied ARDL estimation approach and concluded that ICT contributed positively in the long run in Indonesia. (Untari *et al.,* 2019) also reported the same finding for Indonesia. (Audi & Ali, 2019) analyzed the data of developing and developing countries for the effect of ICT on economic growth. According to the panel data estimation, ICT had positive impact on economic growth in developing countries while they had insignificant effect on economic growth in developed countries. For Mexico, (Garcia, 2019) also found that internet use had negative impact on the economic growth of the country.

ICT and Energy Consumption

There are surprisingly few studies that empirically assess the relationship between ICT and energy use, despite the fact that it has emerged as an important issue in terms of its effects on the economy and the environment. Here is a summary of the findings from empirical analyses examining into how ICT affects energy use. (Dabbous, 2018) explored the nexus between ICT, energy consumption and financial development in MENA countries over 1995–2014 period. Applying CCEMG estimation approach, it was concluded that ICT increased energy consumption whereas financial development had no significant effect on energy consumption. (Saidi *et al.,* 2017) explored the association between ICT and energy consumption in 67 countries over 1990–2012 period belonging to all income group. Applying dynamic panel estimation, ICT had significant positive effect on energy consumption in all panels. (Tunali, 2016) scrutinized the data of EU countries over 1990–2012 period by applying panel ARDL estimation approach, the authors have found that ICT related technologies were related with increased energy consumption. Analyzing the data of China by applying Partial Least Square estimation, (Han *et al.*, 2016) found that ICT had U-shaped association with energy consumption. (Afzal & Gow, 2016) for N-11 countries applied Panel Pooled Mean Group, Mean Group and GMM estimation approaches and concluded that ICT had positive association between energy consumption and ICT. For emerging economies, (Sadorsky, 2012) estimated the effect of ICT on electricity consumption over 1993–2008 period. The analysis findings of GMM estimation revealed the positive association between electricity consumption and ICT. (Lv *et al.,* 2022) explored the nexus between ICT and renewable energy consumption in a panel of 90 countries over 2000-2014 period. According to the findings of spatial spillover effects, the ICT had positive effect on renewable energy consumption. Considering the household data of USA (Martiskainen & Coburn, 2011) also conclude that ICT related technologies were associated with the decline in household energy consumption. In contrast, (Longo & York, 2015) in a panel data analysis concluded that ICT products like mobile phone use, internet use were positively associated with increase in energy consumption.

Literature Gap

Despite growing number of studies in the literature about energy consumption and ICT nexus and economic growth and ICT nexus, few researchers have begin to empirically investigate the potential impact of ICT on economic growth and energy consumption. In addition, earlier researches have analyzed the linear influence of ICT on economic growth and energy consumption, however, the empirical estimation of the above mentioned nexuses at different quantiles is ignored by the researchers.

Model and Variables

To fulfill the study objective which is the assessment of the effect of ICT on economic growth and energy consumption, the first is referred to as the growth model and uses GDP per capita as the dependent variable. The other model is referred to as the energy model and uses energy consumption as the dependent variable. The ICT variable is added as the main explanatory variable in both models. ICT is measured by generating a comprehensive index by using principle component analysis. The details of ICT components are given in Table 2. Moreover, to avoid model misspecification error, we added relevant control variables in the model. The economic growth is taken as the function of ICT, labour force, capital and energy consumption following (Lee & Chang, 2008), (Apergis & Payne, 2009) and (Usman *et al.*, 2021), whereas energy consumption is taken as the function of ICT, economic growth, energy prices and financial development following (Dabbous, 2018; Saidi *et al.*, 2017).

Both of the models in econometric form are given as

$$GDP_t = \beta_0 + \beta_1 ICT_t + \beta_2 EC_t + \beta_3 LAB_t + \beta_4 CAP_t + \varepsilon_t \quad (1)$$

$$EC_t = \beta_0 + \beta_1 ICT_t + \beta_2 GDP_t + \beta_3 EP_t + \beta_4 FD_t + \varepsilon_t \quad (2)$$

All relevant details of the study variables are provided in the following Table 1

Table 1

Data Sources and Variable Measurements

Variables	Acronym	Measurement	Data Sources
Economic growth	GDP	GDP per capita (constant US$ 2015)	WDI
Information and communication technologies	ICT	ICT Index (authors calculation)	ITU, WDI and UN
Energy consumption	EC	Energy consumption equivalent of oil kg per capita	WDI
Labour	LAB	Labour force (total)	WDI
Capital	CAP	Gross fixed capital formation (%)	WDI
Energy prices	EP	Crude oil price (US$ per barrel).	BP
Financial development	FD	Domestic credit to private sector (%)	WDI

Note: ITU=, UN= United Nations, BP= British Petroleum, WDI= World Development Indicators.

Table 2

Digitalization Index Components

Components	Measurement	Data Sources
Fixed telephone subscriptions	Per 100 people	ITU
Fixed broadband subscriptions	Per 100 people	ITU
Mobile cellular subscriptions	Per 100 people	ITU
Individuals using the Internet	% of population	ITU
Telecommunication Infrastructure Index	Index	UN
ITU Online Service Index		UN
Medium and high-tech manufacturing value added	% of manufacturing value added	WDI
E-Participation Index		UN
ICT goods imports	% of total goods export	WDI
ICT goods exports	% of total goods imports	WDI
Per capita value added of service industry	$US/person	WDI

QARDL Estimation

To assess environmental and energy determinants, a variety of techniques have been used in the past, but QARDL presented by (Cho, Kim, & Shin, 2015) has garnered surprisingly little attention. We therefore aim to investigate the cross-quantile long-run effects of ICT on economic growth and energy consumption in China using the QARDL cointegration techniques. The Wald test refers to a practical instrument for evaluating the integration coefficients stability over a wide range of quantiles, and can be used to assess the stability of the integrating association with time. Therefore, we developed the equation below as the framework for our ARDL model.

$$GDP_t = \alpha + \sum_i^p \beta_1 ICT_{t-i} + \sum_i^q \beta_2 EC_{t-i} + \sum_i^r \beta_3 LAB_{t-i} + \sum_i^s \beta_4 CAP_{t-i} + \epsilon_t \quad (a)$$

$$EC_t = \alpha + \sum_i^u \beta_1 ICT_{t-i} + \sum_i^v \beta_2 GDP_{t-i} + \sum_i^w \beta_3 FD_{t-i} + \sum_i^x \beta_4 EP_{t-i} + \epsilon_t \quad (b)$$

Where the error terms of both preceding equations are defined as $GDP_t - E\left[\frac{GDP_t}{w_{t-1}}\right]$ and $EC_t - E\left[\frac{EC_t}{w_{t-1}}\right]$ with the lowest possible υ field consisting of GDP_t, EC_t, ICT_t, LAB_t, CAP_t, FD_t, and EP_t, GDP_{t-1}, EC_{t-1}, ICT_{t-1}, LAB_{t-1}, CAP_{t-1}, FD_{t-1}, EP_{t-1}. p,q.r.s.u.v.w.x represent the lag orders of independent variables specified by Schwarz Information Criterion. ICT, EC, LAB, CAP in equation (a) represent ICT, energy consumption, labour and capital respectively and in equation (b) economic growth, financial development and energy prices are denoted by GDP, FD and EP respectively. According to (Cho *et al.*, 2015), we formatted equation (a) and equation (b) as quantile ARDL below.

$$Q_{\Delta GDPt} = \mu(\tau) + \sum_{i=1}^{p} \sigma_{GDPi}(\tau)\, GDP_{t-i} + \sum_{i=0}^{q} \sigma_{ICTi}(\tau) ICT_{t-i} + \sum_{i=0}^{r} \sigma_{LABi}(\tau)\, LAB_{t-i} + \sum_{i=0}^{s} \sigma_{CAPi}(\tau) CAP_{t-i} + \varepsilon_t(\tau) \quad (c)$$

$$Q_{\Delta ECt} = \mu(\tau) + \sum_{i=1}^{u} \sigma_{ECi}(\tau)\, EC_{t-i} + \sum_{i=0}^{v} \sigma_{ICTi}(\tau) ICT_{t-i} + \sum_{i=0}^{w} \sigma_{FDi}(\tau)\, FD_{t-i} + \sum_{i=0}^{x} \sigma_{EPi}(\tau) EP_{t-i} + \varepsilon_t(\tau) \quad (d)$$

$where\ \varepsilon_t(\tau) = GDP_t - Q_{GDPt}(\frac{\tau}{\delta_{t-1}})$ and $\varepsilon_t(\tau) = EC_t - Q_{ECt}(\frac{\tau}{\delta_{t-1}})$ and 0<τ<1 denote quantiles. We have extended equation © and equation (d) to include more information in an effort to prevent serial correlation, as shown below.

$$Q_{\Delta GDPt} = \mu + \sigma GDP_{t-1} + \rho_{GDP-1} + \pi_{ICT} ICT_{t-1} + \pi_{EC} EC_{t-1} + \pi_{LAB} LAB_{t-1} + \pi_{CAP} CAP_{t-1} + \sum_{i=0}^{p} \sigma_{GDPi} \Delta GDP_{t-i} + \sum_{i=0}^{q} \sigma_{ICTi} ICT_{t-i} + \sum_{i=0}^{r} \sigma_{ECi} EC_{t-i} + \sum_{i=0}^{s} \sigma_{LABi} LAB_{t-i} + \sum_{i=0}^{u} \sigma_{CAPi} CAP_{t-i} + \varepsilon_t(\tau) \quad (e)$$

$$Q_{\Delta ECt} = \mu + \sigma EC_{t-1} + \rho_{EC-1} + \pi_{ICT} ICT_{t-1} + \pi_{EC} GDP_{t-1} + \pi_{FD} FD_{t-1} + \pi_{EP} EP_{t-1} + \sum_{i=0}^{p} \sigma_{ECi} \Delta EC_{t-i} + \sum_{i=0}^{u} \sigma_{ICTi} ICT_{t-i} + \sum_{i=0}^{v} \sigma_{GDPi} GDP_{t-i} + \sum_{i=0}^{w} \sigma_{FDi} FD_{t-i} + \sum_{i=0}^{x} \sigma_{EPi} EP_{t-i} + \varepsilon_t(\tau) \quad (f)$$

The error correction of QARDL can be built and expanded using equation (g) and equation (h) as shown below:

$$Q_{\Delta GDPt} = \mu(\tau) + \rho(\tau) GDP_{t-1} - \beta_{ICT}(\tau) ICT_{t-1} - \beta_{EC}(\tau) EC_{t-1} - \beta_{LAB}(\tau) LAB_{t-1} - \beta_{CAP}(\tau) CAP_{t-1}) + \sum_{i=1}^{p} \sigma_{GDPi}(\tau) \Delta GDP_{t-i} + \sum_{i=0}^{q} \sigma_{ICTi}(\tau) \Delta ICT_{t-i} + \sum_{i=0}^{r} \sigma_{ECi}(\tau) \Delta EC_{t-i} + \sum_{i=0}^{s} \sigma_{LAB}(\tau) \Delta LAB_{t-i} + \sum_{i=0}^{u} \sigma_{CAPi}(\tau) \Delta CAP_{t-i} + \varepsilon_t(\tau) \quad (g)$$

$$Q_{\Delta ECt} = \mu(\tau) + \rho(\tau)(EC_{t-1} - \beta_{ICT}(\tau) ICT_{t-1} - \beta_{EP}(\tau) EP_{t-1} - \beta_{GDP}(\tau) GDP_{t-1} - \beta_{FD}(\tau) FD_{t-1}) + \sum_{i=1}^{p} \sigma_{ECi}(\tau) \Delta EC_{t-i} + \sum_{i=0}^{q} \sigma_{ICTi}(\tau) \Delta ICT_{t-i} + \sum_{i=0}^{r} \sigma_{EPi}(\tau) \Delta EP_{t-i} + \sum_{i=0}^{s} \sigma_{FD}(\tau) \Delta FD_{t-i} + \sum_{i=0}^{u} \sigma_{GDPi}(\tau) \Delta GDP_{t-i} + \varepsilon_t(\tau) \quad (g)$$

The short run potential impact of earlier GDP and EC on present GDP and EC is computed by $\sigma^* = \sum_{i=1}^{p} \sigma_{GDPi}$ and $\sigma^* = \sum_{i=1}^{v} \sigma_{ECi}$, whereas, combined short run effects of earlier and current level of ICT, LAB, CAP, FD and EP are estimated by $\sigma_{ICT} = \sum_{i=1}^{q} \sigma_{ICTi}$, $\sigma_{LAB} = \sum_{i=1}^{r} \sigma_{LABi}$, $\sigma_{CAP} \sum_{i=1}^{s} \sigma_{CAPi}$, $\sigma_{FD} \sum_{i=1}^{u} \sigma_{FDi}$, $\sigma_{EP} \sum_{i=1}^{v} \sigma_{EPi}$.

The following is an estimation of each variable's long-term integration parameters::

$\beta_{ICT^*} = -\frac{\beta ICT}{\rho}, \beta_{LAB^*} = -\frac{\beta LAB}{\rho}, \beta_{LAB^*} = -\frac{\beta CAP}{\rho}, \beta_{CAP^*} = -\frac{\beta FD}{\rho}, \beta_{FD^*} = -\frac{\beta EP}{\rho},$

Using the standard delta technique, the combined short run and long run coefficients are measured, and ECM (ρ) has to be negative. In addition to QARDL, Quantile Granger Causality for determining causal association and Wald test for parameter constancy are also applied.

Results and Discussions

The study uses time series data that requires some preliminary estimation. First of all, Table 3 reports descriptive statistics of all study variables including mean, standard deviation and data range. In addition, Jarque-Bera test for normality rejects the null hypothesis of normal distribution showing that all of the series are not following normal distribution.

Table 3

Summary or Descriptive Statistics

Variables	Mean	Min	Max	Std. Dev.	J-B Stats
GDP	5300.6	1520.02	11188.3	3108.6	15.099***
ICT	0.453	11.09	56.90	3.667	23.981***
EC	1408.8	866.89	2224.3	516.84	11.320***
LAB	7623823	6811345	7955723	3434523	18.304***
CAP	39.0425	31.003	44.518	4.6334	32.452***
FD	124.81	84.206	182.868	24.654	12.425***
EP	22.87	25.89	71.56	37.90	14.661***

Where *** denotes P<0.05.

Time-series data may experience stationarity issues. As a result, it is advantageous to examine the unit root characteristics of the data before using any regression technique. Our study uses the ADF unit root test as well as the Zivot and Andrews (ZA) unit root test for this purpose. The findings of the tests are provided in Table 4. The findings indicate that the series contain unit root at level in both tests and become stationary after differencing.

Table 4

ZA and ADF Unit Root Test Results

Variables	ADF	ADF (delta)	ZA	Break Year	ZA (delta)	Break Year
GDP	-1.246	-1.344***	-0.276	1995 Q3	-6.332***	1999 Q1
ICT	-1.765	-2.436***	-1.224	2001 Q1	-4.333***	2002 Q4
EC	-1.632	-3.829***	1.245	2004 Q4	-4.346***	2009 Q1
LAB	-0.557	-4.312***	-1.354	2007 Q3	-5.243***	2013 Q1
CAP	-0.322	-3.433***	-3.350	2016 Q1	-4.043***	2015 Q4
FD	-1.987	-4.555***	-2.465	2002 Q2	-4.341***	2010 Q1
EP	-0.854	-3.998***	1.332	2008 Q4	-3.913***	2018 Q1

*** denotes =P<0.05

QARDL Results for Model 1

The finding compels us using QARDL approach. Results of the QARDL regression approach for Model 1 are shown in Table 5. The findings for constant term are shown by the α_* parameter and they show a significant constant term at all quantiles. The ECM findings are shown by the ρ parameter, and they show that it is significantly negative at all quantiles. It confirms that the dependent variable (GDP) and independent factors (LAB, CAP, ICT and EC) have a long-term relationship. the β parameter show the long-run coefficients, whereas the short-run coefficient are shown by the λ parameter. In terms of long run findings, the coefficient of ICT is significant and positive at all quantiles (0.05–0.95). The significant positive coefficient indicates that increase in ICT increases GDP in China. The finding is justifiable in the light of previous studies (Toader *et al.,* 2018), (Usman *et al.,* 2021) and (Fernandez-Portillo *et al.,* 2020) who reported the same findings arguing that more ICT adoption must boost economic growth by promoting competition that leads to the creation of new goods, services, and business models and accelerating the adoption of novel processes. ICT development and penetration promotes economic growth directly by improvements in productivity and indirectly by materialization of externalities and creation of innovations (Fernandez-Portillo *et al.,* 2020). Next, the energy consumption coefficient is also significantly positive over the quantile range (0.05-0.70) implying that increase in energy consumption leads to increase in economic growth. The finding proves the energy led growth hypothesis according to which unidirectional causality is present between energy consumption and economic growth. It suggests that energy consumption, in addition to labour and capital, plays a significant influence in economic growth. (Omri, 2014), (Zaman & Abd-el Moemen, 2017), (Alshehry & Belloumi, 2015) and (Elfaki *et al.,* 2021) strongly support our findings.

Table 5

QARDL Findings for Model 1

Quantiles	Constant	ECM	Long Run				Short Run				
(τ)	$\alpha_*(\tau)$	$\rho_*(\tau)$	$\beta_{ICT}(\tau)$	$\beta_{EC}(\tau)$	$\beta_{LAB}(\tau)$	$\beta_{CAP}(\tau)$	$\varphi_1(\tau)$	$\omega_0(\tau)$	$\lambda_0(\tau)$	$\theta_0(\tau)$	$\gamma_0(\tau)$
0.05	0.012	-0.334***	0.340***	0.330**	0.520	0.114	0.221***	0.492**	0.488***	0.235	0.392
	(0.000)	(-4.044)	(2.436)	(2.033)	(2.634)	(0.311)	(11.273)	(2.959)	(9.971)	(2.364)	(3.633)
0.10	0.022	-0.131***	-0.345*	0.234***	0.634	0.332	0.242***	0.918**	0.437***	3.243	0.256
	(0.005)	(-4.244)	(2.543)	(3.073)	(2.238)	(0.338)	(14.320)	(2.252)	(4.011)	(3.554)	(4.566)
0.20	0.028	-0.119***	0.432***	0.136***	0.435	0.544	0.421***	0.763**	0.248**	0.234*	0.347*
	(0.003)	(-4.021)	(1.377)	(4.140)	(2.348)	(0.432)	(10.987)	(2.996)	(2.779)	(2.438)	(4.347)
0.30	0.015	-0.721***	0.645**	0.321***	0.475*	0.520	0.432***	0.929**	0.448**	0.325*	0.224*
	(0.003)	(-4.336)	(3.455)	(4.048)	(2.438)	(0.081)	(4.246)	(1.765)	(3.911)	(2.893)	(3.943)
0.40	0.013	-0.443***	0.225**	0.218***	0.365*	1.532*	0.651***	0.692	0.440*	0.244*	0.444*
	(0.002)	(-4.426)	(2.144)	(3.332)	(2.646)	(2.981)	(4.698)	(2.535)	(4.583)	(2.754)	(4.544)
0.50	0.023	-0.424***	0.454**	0.125**	0.951	0.523	0.432***	0.820	0.540*	0.331*	0.436*
	(0.011)	(-4.336)	(2.956)	(3.034)	(0.082)	(4.832)	(2.134)	(0.927)	(3.878)	(2.941)	(4.467)
0.60	0.032	-0.124***	0.134**	0.834***	0.549	0.431	0.693***	0.348	0.242*	0.345**	0.467**
	(0.004)	(-3.533)	(3.944)	(2.036)	(0.091)	(4.422)	(6.787)	(3.254)	(4.570)	(2.648)	(2.435)
0.70	0.003	-0.245***	0.445***	0.254***	0.053	0.332	0.687***	0.428	0.217	0.335**	0.445**
	(0.004)	(-5.040)	(2.544)	(2.334)	(0.931)	(3.331)	(3.664)	(4.384)	(3.420)	(2.094)	(2.456)
0.80	0.063	-0.451***	0.546***	0.93	0.635	0.345	0.361***	0.250	0.089	0.125**	0.555**
	(0.004)	(-4.439)	(3.231)	(0.213)	(0.009)	(2.249)	(4.036)	(3.296)	(4.519)	(2.849)	(2.821)
0.90	0.024	-0.254***	0.530***	0.244	0.057	0.147	0.899***	0.358	0.529	0.211**	0.431**
	(0.002)	(-3.517)	(2.534)	(0.035)	(0.293)	(3.234)	(3.272)	(3.357)	(4.663)	(2.999)	(4.321)
0.95	0.012	-0.537***	0.163***	0.017	0.109	0.249	0.648***	0.096	0.774	0.525**	0.235**
	(0.005)	(-5.232)	(3.223)	(0.013)	(0.003)	(2.443)	(7.491)	(7.297)	(4.470)	(2.976)	(3.746)

*Between brackets are the t statistics. *, **, and *** are levels of significance at 10, 5, and 1 percent, respectively.*

Author Estimations

For control variables, labour force is having statistically positive and significant mpact but only at lower range of quantiles (0.05–0.40), while the coefficient of capital is significantly positive only over (0.4 to 0.95) range of quantiles confirming the fact that labour is the main important determinant of the economic growth according to traditional growth models like Cobb Douglas Production function and consistent with the results of (Ayres & Voudouris, 2014), (Solarin, 2020), (C. L. Chang & Fang, 2022) and (Nweke *et al.,* 2017). The finding implies that capital formation and labour force enhance the production capacity of the economy and increases the economic growth. The findings of the short run analysis are also given in Table 5. The coefficients of ICT and energy consumption are statistically significant and positive at all quantiles. However, the effect of labour and capital is also positive and significant at all quantile unlike long run estimation.

After QARDL estimation, Quantile Granger Causality test and Wald test are also applied. According to the findings of Granger Test (reported in Table 6), bidirectional causal association is present between GDP, ICT, EC, LAB and CAP over all quantiles. The Wald test findings are shown in Table 7. This test aids in analyzing asymmetries between variables. The Wald test's null hypothesis indicates that there are no nonlinearities or asymmetries in the relationship between the variables. In this study, both the long-term and the short-term null hypotheses are accepted for EC, ICT, LAB, CAP and GDP. The results confirm that variables have symmetric and linear relationships with GDP as a result. Additionally, the ECM (ρ) value is statistically significant, supporting the asymmetric relationships between the variables.

Table 6

Findings of Wald Test for Model 1

Series	Wald-stat [Prob-Value]
P	22.381***
	[0.030]
B_{ICT}	14.231***
	[0.040]
B_{EC}	16.222***
	[0.010]
B_{LAB}	20.978***
	[0.000]
B_{CAP}	14.777*** [0.000]
φ_1	16.564***
	[0.032]
ω_0	23.406***
	[0.000]
λ_0	25.323***
	[0.008]
θ_0	20.335***
	[0.000]
p_1	17.221***
	[0.000]
γ_0	22.535***
	[0.035]

Table 7

Findings of Quantile Granger Causality Test for Model

Quantiles	**ΔGDP_t ↓ ΔICT_t**	**ΔICT_t ↓ ΔGDP_t**	**ΔGDP_t ↓ ΔEC_t**	**ΔEC_t ↓ ΔGDP_t**	**ΔGDP_t ↓ ΔLAB_t**	**ΔLAB_t ↓ ΔGDP_t**	**ΔGDP_t ↓ ΔCAP_t**	**ΔCAP_t ↓ ΔGDP_t**
[0.05-0.95]	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
0.05	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
0.10	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
0.20	0.000	0.000	0.000	0.000	0.000	0.000	0.067	0.000
0.30	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
0.40	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
0.50	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
0.60	0.000	0.000	0.000	0.000	0.000	0.000	0.009	0.000
0.70	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
0.80	0.000	0.000	0.000	0.000	0.000	0.000	0.040	0.000
0.90	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
0.95	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000

Source: Authors Estimation

QARDL Results for Model 2

Now we proceed towards long and short run QARDL estimation for Model 2 or energy consumption model and findings are provided in Table 8. Like Model 1, The findings for constant term are shown by the α_* parameter and they show that constant term is significant in all quantiles. The results of ECM are shown by the ρ parameter, and they show that it is significant and has a negative sign in all quantiles. This finding confirms that the dependent variable (EC) and independent variables (ICT, GDP, EP, FD) have a long-term relationship. First of all, the findings of long run analysis are presented by β which indicate that the coefficient of ICT is positive and significant over entire quantile range (0.05–0.95). The positive coefficient indicates the presence of long run positive association between ICT and energy consumption. The finding is consistent with (Lange, Pohl, & Santarius, 2020), (Han *et al.*, 2016), (Tunali, 2016) and (Dabbous, 2018). The finding is justifiable as ICT uses energy, especially as equipments need power to operate (Sadorsky, 2012). The (IEA., 2009) came to the conclusion that electronic gadgets had significantly contributed to the overall growth of energy demand and issued a warning that they will soon rank among the top energy-consuming categories. The coefficient of financial development is negative over entire quantile range indicating that financial development possesses negative association with energy consumption in China. The finding is consistent with the hypothesis that improving the financial system's efficiency would increase the amount of funds available for energy-substitution channels like the renewable energy industry, which reduces energy consumption. From previous literature, (Dasgupta, Hong, Laplante, & Mamingi, 2006), (Chiu & Lee, 2020) and (Gaies *et al.*, 2019) provide evidence for our finding.

Table 8

QARDL Findings for Model 2

Quantiles	**Constant**	**ECM**	**Long Run Estimation**				**Short Run Estimation**				
(τ)	**$\alpha_*(\tau)$**	**$\rho_*(\tau)$**	**$\beta_{ICT}(\tau)$**	**$B_{GDP}(\tau)$**	**$B_{FD}(\tau)$**	**$B_{EP}(\tau)$**	**$\varphi_1(\tau)$**	**$\omega_0(\tau)$**	**$\lambda_0(\tau)$**	**$\theta_0(\tau)$**	**$\gamma_0(\tau)$**
0.05	0.055	-0.562***	0.451***	0.421**	-0.240	-0.333	0.388***	0.222**	0.309***	-0.346	-2.376
	(0.000)	(-5.046)	(4.567)	(4.432)	(-2.666)	(-0.114)	(1.411)	(4.549)	(2.734)	(-3.624)	(-0.655)
0.10	0.033	-0.155***	0.411*	0.456***	-0.344	-0.211	0.124***	0.214**	0.335***	-1.433	-1.546
	(0.003)	(-4.661)	(5.556)	(4.056)	(-3.348)	(-0.008)	(4.230)	(4.552)	(2.345)	(-3.564)	(-0.543)
0.20	0.045	-0.469***	0.314***	0.234***	-0.435	-0.476	0.231***	1.643**	0.449**	-0.354*	-0.411*
	(0.001)	(-3.111)	(2.341)	(3.243)	(-2.345)	(-0.021)	(3.817)	(3.594)	(3.719)	(-2.378)	(-0.112)
0.30	0.094	-0.324***	0.424**	0.243***	-0.545*	-0.230	0.321***	0.439**	0.238**	-0.245*	-0.413*
	(0.002)	(-4.642)	(4.515)	(3.143)	(-2.481)	(-0.031)	(3.446)	(3.645)	(4.134)	(-2.993)	(-0.012)
0.40	0.033	-0.357***	0.531**	0.354***	-0.635*	-1.332	0.614***	0.887***	0.255*	-0.433*	-1.578*
	(0.005)	(-2.456)	(4.454)	(4.372)	(-2.455)	(-0.841)	(3.938)	(2.443)	(3.843)	(-2.524)	(-2.424)
0.50	0.045	-0.351***	0.299**	0.456**	-0.651	-0.233	0.332***	0.325***	0.467*	-0.413*	-0.324*
	(0.080)	(-4.346)	(2.974)	(3.532)	(-3.034)	(-0.421)	(3.344)	(3.023)	(3.134)	(-0.480)	(-2.641)
0.60	0.046	-0.930***	0.300**	0.451***	-0.419	-0.321	0.943***	0.438***	0.444*	- 0.485**	- 0.673**
	(0.007)	(-4.375)	(4.120)	(3.346)	(-2.291)	(-4.987)	(4.897)	(2.113)	(4.987)	(-0.499)	(-4.444)
0.70	0.225	-0.412***	0.345***	0.443***	-0.254	-0.213	0.826***	0.321***	0.455	- 1.555**	2.533**
	(0.0078)	(-4.243)	(4.446)	(3.498)	(-3.941)	(-3.087)	(3.451)	(4.543)	(4.250)	(-0.007)	(0.431)
0.80	0.053	-0.331***	0.432***	0.511	-0.335	-0.421	0.442***	0.534***	0.283	- 0.265**	1.235**
	(0.002)	(-3.353)	(3.344)	(3.007)	(-3.349)	(-2.267)	(3.132)	(3.445)	(4.114)	(-0.111)	(2.567)
0.90	0.091	-0.534***	0.231***	0.276	-0.154	-0.332	0.495***	0.445***	0.956	- 2.219**	1.345**
	(0.006)	(-2.147)	(2.334)	(3.234)	(-3.943)	(-3.354)	(4.712)	(3.885)	(4.345)	(-0.003)	(0.022)
0.95	0.036	-0.348***	0.351***	0.113	-0.193	-0.459	0.438***	0.134***	0.408	- 0.022**	0.214**
	(0.004)	(-4.352)	(5.098)	(0.543)	(-4.434)	(-2.313)	(4.951)	(4.955)	(2.717)	(-0.074)	(0.013)
	Between brackets are the t statistics. *, **, and *** are levels of significance at 10, 5, and 1 percent, respectively. Author Estimations										

The coefficient of GDP is also positive and statistically significant at all quantiles (0.05–0.95) showing that GDP adds to energy consumption consistent with (Wang *et al.*, 2019), (Tunali, 2016; Usman *et al.*, 2021). According to estimates for GDP, increase in economic activities is associated with rising energy consumption in China. In addition, with increase in income, China's inhabitants are purchasing more energy consuming products like light-emitting diodes, air conditioners, electric ovens, refrigerators, etc., which would ultimately result in higher energy consumption. And last, energy price has negative impact on energy consumption over medium to higher quantiles (0.60–0.95) only. The negative coefficient is indicating the adverse influence of energy prices on energy consumption. The finding is in line with (Yuan, Liu, & Wu, 2010), (Wang *et al.*, 2019) and (Komal & Abbas, 2015). This conclusion supports the economic hypothesis that when a commodity's price rises, its consumption declines (Komal & Abbas, 2015). The last four columns of Table 9 show short run findings of the Model 2. According to the coefficients, the relationship between energy consumption and its determinants is the same as in the long run. However the significance of some variables varies at different quantiles as compare to long run. in the short run, ICT and GDP has positive and significant effect on all quantiles (0.05–0.95), but financial development has significant impact only at lower quantiles (0.05–0.40) while energy prices had significant impact only over 0.40–0.80 quantiles.

Just like Model 1, we have applied Quantile Granger Causality test and Wald test for Model 2 also. Table 10 provides the results for Granger Causality test revealing that bidirectional causal association is present between energy consumption and ICT, GDP, FD and EP. Wald test findings for parameter constancy provided in Table 9 provide the evidence for the acceptance of null hypothesis of no asymmetric and non linear association between energy consumption and all variables at quartiles in the long and short run both.

Table 9

Findings of Wald Test for Model 2

Series	**Wald-stat [Prob-Value]**
P	26.809***
	[0.000]
B_{ICT}	15.000***
	[0.000]
B_{GDP}	12.098***
	[0.000]
B_{FD}	10.709***
	[0.000]
B_{EP}	47.033***
	[0.000]

Series	**Wald-stat [Prob-Value]**
φ_1	19.098***
	[0.002]
ω_0	13.496***
	[0.000]
λ_0	12.029***
	[0.000]
θ_0	14.750***
	[0.000]
ρ_1	13.109***
	[0.000]
γ_0	11.777***
	[0.000]

Table 10

Findings of Quantile Granger Causality Test for Model 2

Quantiles	$\Delta EC_t \downarrow \Delta ICT_t$	$\Delta ICT_t \downarrow \Delta EC_t$	$\Delta EC_t \downarrow \Delta GDP_t$	$\Delta GDP_t \downarrow \Delta EC_t$	$\Delta EC_t \downarrow \Delta FD_t$	$\Delta FD_t \downarrow \Delta EC_t$	$\Delta EC_t \downarrow \Delta EP_t$	$\Delta EP_t \downarrow \Delta EC_t$
[0.05-0.95]	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
0.05	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
0.10	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
0.20	0.000	0.000	0.000	0.060	0.000	0.000	0.000	0.000
0.30	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
0.40	0.000	0.000	0.000	0.000	0.000	0.050	0.000	0.000
0.50	0.000	0.077	0.000	0.000	0.000	0.000	0.000	0.000
0.60	0.000	0.000	0.000	0.000	0.000	0.000	0.009	0.000
0.70	0.000	0.000	0.000	0.00	0.000	0.000	0.000	0.000
0.80	0.000	0.000	0.000	0.000	0.009	0.000	0.000	0.000
0.90	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
0.95	0.000	0.022	0.000	0.000	0.000	0.000	0.000	0.000

Conclusion and Policy Implications

The present study has two main purposes: First is to estimate the role of ICT in economic growth and second purpose is to explore the role of ICT in energy consumption. Correspondingly, two different models have been proposed: Model 1 for economic growth and Model 2 for energy consumption. To estimate the nexus empirically, time series data spanning over 1995–2021 period is estimated by applying QARDL approach. The study findings indicate the positive and significant effect of ICT on economic growth as well as on energy consumption at all quantiles in both models of the study. Moreover, Quantile Granger Causality test provide evidence for the bidirectional causal association between ICT, energy consumption and economic growth. The findings of Wald test for both models provide evidence for the parameter constancy at all quantiles in both of the models showing that variables have linear and symmetric association with economic growth and energy consumption. Based on our research, we emphasize that government policies should place a high priority on the development of ICT infrastructure (by supporting higher investment for ICT so as to give simple access to such technologies) in order to boost economic growth. Therefore, elements pertaining to training and intended to fully exploit ICT might be incorporated into public policy initiatives to benefit the economy. ICTs have a considerable impact on the economic development of China; hence the political authorities should enhance investment in this sector. But the authorities should focus on the investment in energy efficient ICT products. Energy-efficient ICT goods reduce energy consumption while also have positive environmental consequences as a result of their low energy use. We recommend future reserachers to broaden the scope and addition of more relevant explanatory variables in their studies.

Contributions

All these authors contributed equally as co-first authors.

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