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Does Digitalization Lead to Environmental Sustainability and Energy Efficiency in China?

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In the past 20 years, there has been an increased focus on the connection between investments in digitalization, environment, and economic growth, however the effects of digitalization on energy efficiency in developing nations have received little attention in empirical researches. therefore, the goal of current research is to study the effect of digitalization on environmental sustainability and energy efficiency in China over 1995–2020. For this purpose, two separate models are formulated with energy efficiency and CO2 emissions as dependent variables and digitalization (measured by ICT technologies) as the explanatory variable. The study applies three time series approaches namely, Dynamic Ordinary Least Square (DOLS), Fully Modified Ordinary Least Square (FMOLS), and Canonical Cointegration Regression (CCR) to empirically estimate the study objectives. The study findings show that ICT plays positive role in promoting energy efficiency and environmental sustainability as coefficient of ICT is negative in both models. It was concluded from the findings that ICT sector has positive implications in terms of energy and environment in China. The study recommends the Chinese government and policy makers to pay attention and device effective policies for promotion of ICT sector in the country.

Keywords: *Digitalization; Energy Efficiency; CO2 Emission; China; FMOLS, DOLS; CCR.*

Introduction

A key component of the economic ecosystem is energy. Energy is a crucial component of human survival and growth, and it also plays a role in a nation's economic prosperity and security. However, due to the industrialization and modernizing that have occurred so quickly, humanity have already used nearly half of the fossil fuels like oil, natural gas and coal that have been stored in the earth, and this trend of increased energy use is continuing (Z. M. Chen & Chen, 2011). China is the one of the largest developing countries of the world, and it consumes the most energy overall. From 571 million tons to 4.64 billion tons of standard coal between 1978 and 2018, China outpaced nations. The economic growth has been somewhat aided by energy consumption, particularly during the early stages of industrialization in China, and this trend is more pronounced today (Matthew *et al.*, 2023; Wu, Hao, & Ren, 2020). However, China's environmental quality has drastically declined as a result of the country's ongoing increase in overall energy consumption. The fraction of major cities' air quality that was above standard in 2018 was 64.2 %. China has a complete score of 50.74 on the Global Environmental Performance Index in 2018, placing it 120th overall and 177th in the air quality rankings out of 180 countries and areas. In addition to being a significant barrier to China's economy's sustainable development, environmental pollution brought on by energy consumption also causes China to suffer massive economic losses (Amaliyah & Zakhra, 2022; Ballestar *et al.*, 2021; Bari *et al.*, 2021; Bridi & Al Hosani, 2022; Miao *et al.*, 2020). The economy of China is currently going through a crucial stage of economic change and industrial improvements. Thus, one essential issue that is necessary to be resolved in China's present environmental sustainability process is how to support the sustainable growth of the economy, environment and energy (X. Chen *et al.*, 2023; Dai *et al.*, 2022; Hantoush *et al.*, 2022; Kielanowicz *et al.*, 2023; Ren *et al.*, 2021). The fourth industrial revolution has transformed the global economy into a digital one (Abbasi *et al.*, 2022; Bag *et al.*, 2020; Hasani & Pahamzah, 2022; Hmelak *et al.*, 2021; Kim *et al.*, 2022; Kurniawan *et al.*, 2022). Consequently, it is anticipated that investing in digital technology will lead to improved macroeconomic performance. The effect of the age of digital technology on energy sector, which makes up a significant portion of the economy, cannot be ignored (Abbasi *et al.*, 2022; Hao *et al.*, 2022; Hereth, 2022; Husaini & Lean, 2022; K. Lee *et al.*, 2021; Leikuma-Rimicane *et al.*, 2022). One of these concerns is the impact of digitalization on energy efficiency in developing nations. Digitalization is already helping energy systems in terms of sustainability, production, accessibility, and safety. Digitalization speeds up the decline in energy intensity, according to (Lougheed, 2022; Ngoc, 2022; Noor, 2022; Olaleye *et al.*, 2022; Ren *et al.*, 2021). Operating digital products and incorporating digital systems into other businesses on the one side consume more energy. On the other side, digitalization uses less energy because it can replace physical processes and has the potential to improve the industrial process (Boni, 2022). The internet, with the aid of technological breakthroughs, may improve and optimize energy consumption systems as well as significantly increase energy efficiency. This will lead to the construction of a sustainable energy platform to better allocate energy resources (Abbasi *et al.,* 2022; Hosan *et al.,* 2021; Orwig, 2021; Peternel & Gress, 2021; Prabowo *et al.,* 2022; Prasetyo *et al.,* 2022). ICT's overall effect on energy use is thus still unclear. Therefore, determining how digitalization affects energy intensity is one of the key goals of this paper. Governments can use the findings to plan economic growth, distribute and utilize energy sources, and promote long-term social and economic development (Sari & Vitalli, 2023).

Despite extensive global documentation of the potential benefits of digitization, the environmental effects of ICT have received little attention. Consequently, there is still no clear connection between digitalization and environmental sustainability (Gandhi *et al.,* 2022). Some research concluded that the rapid development of digitalization has improved the environmental quality by reducing CO2 emissions, while other found that increased use of digital gadgets has worsened the environment. Additionally, the literature now available demonstrates the diverse effects of digitalization on CO2 emissions in both developing and industrialized nations, (Al-Mulali *et al.,* 2015; Higon *et al.,* 2017; Rahi, 2022; Sogaxa & Simpeh, 2022; Sriyakul & Chankoson, 2022; Xiao *et al.,* 2023; Zhang *et al.,* 2023).

All equipment and communications tools (such as radio, tv, mobile phones, processors, and satellite systems) that let people access, transmit, or retain information are included under the umbrella term of ICT (Pradhan *et al.,* 2018). ICT users now have considerably faster, larger, and more comprehensive access to information than they did previously (Erdmann & Hilty, 2010; Peternel & Gress, 2021). Digital infrastructure is thought to enhance service delivery, create transparency, and foster communication between the government and population (Lu, 2018). ICT adoption has also significantly decreased production costs, improved efficiency in resource allocation, and sparked much higher investment in several economic sectors (Khan *et al.,* 2020). Digitalization and ICT affect the environment negatively as well as positively (Mendez-Suarez & Danvila-del-Valle, 2023). ICT use, disposal, and production have a negative ecological impact and raise CO2 emissions from power generation. ICT use directly affects power demand, but it also increases energy use in the production of equipment and the maintenance of infrastructure maintenance, such as datacenters and server parks. On the other side, ICT may cut emissions by creating smarter industrial processes, transportation systems, cities, and electricity grid (Higon *et al.,* 2017). This is mostly due to the fact that the advancement of information technology has the potential to compel businesses and corporations to embrace environmentally friendly production methods in place of older, energy-intensive ones. This has the effect of changing the industrial structure (Cheng *et al.,* 2019).

The purpose of the current research is to estimate that what role digitalization can play in environmental sustainability as well as in energy efficiency in China over 1995-2020 period. digitalization has expanded quickly in China since the beginning of the 21st century (X. Yuan, 2022). This is attributed to a process of technological advancing and ICT initiatives initiated by the Chinese government. For the first time in 2003, mobile phone subscribers outnumbered fixed-line users. The total investment in ICT in 2014 is almost 2.5 times that of 2003. However, there is currently a shortage of empirical studied on the relation between Chinese digitalization and energy efficiency and environmental sustainability (Wang & Han, 2016). Examining how investments in digital infrastructure affect energy usage is a critical concern that needs to be resolved as China enters the early stages of an information society around 2020.

The following are some potential new ideas and contributions made by this paper. i) The inclusion of digital components in the research model of environmental sustainability and energy efficiency somewhat broadens the scope of the study of environmental and energy economics. Particularly this is a novel contribution in China context as the relationship between digitalization and energy efficiency and digitalization and environmental sustainability is lacking in China ii) The three dimensions of digital penetration, fixed broadband subscriptions, fixed telephone subscriptions and fixed mobile phone subscription make up the evaluation system for the digital development level. The digitalization level in China is calculated and analyzed using the Principle Component Analysis method. iii) In the empirical analysis, the study uses FMOLS, DOLS and Canonical Cointegration regression estimations that make the study unique in methodological aspects also.

The remainder of the paper is ordered as follows. An overview of the literature is given in Section 2. Model, data, variables and estimation methodology is presented in Section 3. The Section 4 provides discussion and the findings. conclusion and associated policy recommendations are presented in Section 5 last.

Existing Literature Review

The purpose of ICT spread is to establish efficient allocation of resources, and energy industry is not an exception. As a result, a significant body of literature has examined the relationship between digitalization and renewable energy use as well as how development of digital technologies affects the efficiency of energy consumption as a whole. The spread of ICT can cut down on global energy desecrate by boosting both economic efficiency and energy consumption. Zhao, Hafeez, and Faisal (2022) studied the effect of ICT technologies in environmental sustainability and energy efficiency in emerging Asian countries. The findings of panel ARDL and Pooled Mean Group estimation revealed that ICT technologies impact energy efficiency positively and carbon emissions negatively. (Wu *et al*., 2021) studied the role of ICT in green total energy efficiency in different provisions of China over 2006-2017 period using panel spatial Durbin model and findings indicated that a non linear link existed between green factor total energy efficiency and ICT. (Hao *et al*., 2022) also explored the role of ICT development on green total factor energy efficiency at provisional level and observed that ICT had positive impact on green factor total energy efficiency moderated by environmental regulations. (Wang & Han, 2016) considered provisional data of China to study the impact of ICT infrastructure on energy intensity. Applying Driscoll-Kraay Standard error, the authors found that ICT decreased energy intensity in the long run.

Han, Wang, Ding, and Han (2016) studied the role of ICT sector in energy consumption of China. According to the results of ARDL-ECM approach, the ICT sector was found to reduce energy consumption in China. Ishida (2015) studied the nexus between energy consumption, economic growth and ICT. Applying ARDL Bound testing approach, the authors found insignificant impact of ICT on economic growth but negative and significant impact on energy consumption. Applying Dynamic System-GMM estimation (Bridi & Al Hosani, 2022; Xu, Zhong, & Li, 2022) explored the effect of ICT on energy consumption, energy intensity and optimization of energy structure globally and found that ICT reduced energy consumption and energy intensity and there was positive moderating impact of technological innovations and human development on energy-ICT relationship. Wen, Jiang, and Zheng (2022) considered the developing countries to study the nexus between corporate energy intensity and ICT over 2006–2020 period. The results indicated positive contribution of ICT in reducing energy intensity of manufacturing corporations. (Lin & Huang, 2023) scrutinized the data for 227 cities of China over 2011–2019 period and studied the impact of digitalization on electricity intensity. Panel smooth transition model revealed that ICT promoted electricity intensity in Chinese cities.

Digitalization and environmental sustainability nexus has attracted the attention of researchers extensively and mixed conclusions are provided by previous studies. For instance, (Higon *et al.*, 2017) studied the effect of ICT technologies on carbon emissions for a global panel of 142 countries. The results of OLS, Pooled OLS and Driscoll-Kraay standard errors indicated that in developed countries, ICT promoted CO2 emission reduction. (Khan *et al.*, 2020) analyzed the ICT's role in CO2 emission in 91 advanced and developing countries by applying Pooled Mean Group, Fixed Effects and GMM estimation approaches. ICT affected CO2 emission reduction positively in developed economies but had opposite findings for developing economies. (N'dri, Islam, & Kakinaka, 2021) also studied 58 developing countries panel to estimate the nexus between ICT and CO2 emission and by applying Poole Mean Group analysis, favourable impact of ICT was found on CO2 emission reduction in low income countries whereas ICT was found to exacerbate CO2 emission in higher income countries. (Asongu, Le Roux, & Biekpe, 2018) studied that what role ICT technologies could play in environmental sustainability of Sub Saharan African countries. The authors applied GMM estimation approach and concluded no significant impact of ICT on CO2 emission in the selected countries. (Cheng *et al.*, 2019) studied the nexus between ICT development and environmental pollution in spatial perspective in 285 cities of China. The authors found that information technology had significantly increased CO2 emission in the Chinese cities. (Lee & Brahmasrene, 2014) considered the panel data for ASEAN countries in order to estimate the impact of ICT on carbon emissions and concluded the positive contribution of ICT in aggravating carbon emissions in ASEAN countries. Taking the panel data of emerging countries, (Ozcan & Apergis, 2018) applied Augmented Mean Group estimation approach and concluded that internet use had positive contribution in carbon emissions reduction in the countries. Taking a panel of OECD countries, (Salahuddin *et al.*, 2016) also explored the nexus between internet use and environmental pollution and found that internet use did not enhance environmental pollution in OECD countries from Pooled Mean Group estimation. (Al-Mulali *et al.*, 2015) studied the impact of internet retailing on CO2 emission in developed and developing countries. According to the findings of the study from GMM estimation, internet retailing had negative effect on CO2 emission in industrialized countries while it had insignificant effect on CO2 emission in developing economies.

Literature Gaps

The review of above studies shows that previous studies estimated the role of digitalization on environmental quality and energy efficiency in many countries and panel of countries including China. But studies are micro level studies covering different cities or provisions of China. To our best knowledge, none of the earlier studies analyzed the relationship between digitalization, environmental sustainability and energy efficiency at macro or national level. The study tries to fill in this gap present in previous literature.

Model, Data and Empirical Methodology

To estimate the study objectives which are the empirical assessment of energy efficiency and environmental sustainability in China, two models are formulated. Model 1 is energy efficiency model and model 2 is environmental sustainability model. Digital technologies serve as the explanatory variable in both models. To measure it, we constructed a comprehensive index comprising of three measures of ICT technologies using Principle Component Analysis. In addition, the study includes relevant control variables in both models to avoid omitted variable bias.

We formulate the functional form of both models as

Model 1: (Energy efficiency model)

EF = f (ICT, GDP, EP, TO, IV) (1)

Model 2: (Environmental sustainability model)

CO2 = f (ICT, GDP, ET, TO, IV) (2)

Where the econometric expressions for both models are given in equation 3 and equation 4 below

$$EF_t = \alpha_0 + \beta_1 ICT_t + \beta_2 GDP_t + \beta_3 EP_t + \beta_4 TO_t + \beta_4 IV_t + \mu_t \quad (3)$$

$$CO2_t = \alpha_0 + \beta_1 ICT_t + \beta_2 GDP_t + \beta_3 ET_t + \beta_4 TO_{it} + \beta_4 IV_{it} + \mu_{it} \quad (4)$$

Time series data spanning over 1995-2020 period is used to estimate both models in China. Further details of the study variables or series are presented in Table 1 below.

Table 1

Variables, Measurement and Sources of Data

Variables	Abbreviation	Measurement	Data Sources
Carbon dioxide emission	CO2 emission	CO2 emission (kiloton)	WDI
Energy efficiency	EEF	Gross domestic product /energy consumption (Expressed as US dollars equivalent per kilograms of oil at constant 2017 prices)	WDI
Economic Growth	GDP	Gross domestic product (constant US$ 2015)	WDI
Industrial Value Added	IV	Industrial value added constant (2017 US$ prices).	WDI
Trade Liberalization	TO	Trade as % of GDP	WDI
Ecological technologies	ET	Environmental Related Technologies (% of all technologies)	OECD
Energy price (Oil Price)	EP	Crude oil price (US$ per barrel).	BP Statistics (2021)
Industrial Value Added	IV	Industrial value added constant (US$ 2017 prices).	WDI

Estimation Techniques

The study intends to estimate the effect of each independent variable primarily on China's environmental quality and energy efficiency. In this regard, we must make use of a impartial and effective estimator. So, in accordance with (Deng, 2022) we employed three estimation strategies. These methods include the CCR offered by (Park, 1992), FMOLS, and DOLS provided by (Pedroni, 2001). The two methods mentioned above use different methodologies, namely parametric and non-parametric ((DOLS & FMOLS) approaches. Moreover, due to their greater effectiveness in addressing both serial correlation and endogeneity issues, these are consistent assessments of the long-run assessment. Additionally, the DOLS approach is effective for time series evaluation because it addresses the non-stationarity problem. Moving ahead, equation (5) and (6) might be used to present FMOLS and DOLS, respectively, in equation form.

$$\widehat{\emptyset} = \left[\frac{\beta}{\hat{\gamma}}\right] = \left(\sum_{t=2}^{T} Z_t Z_t'\right)\left(\sum_{t=2}^{T} Z_t y_t^{+} - T\left[\frac{\overset{\lambda}{12}}{0}+\right]\right) \quad (5)$$

Where Z_t is ′ (X'_t, D'_t). the analysis of the FMOLS estimation technique heavily relies on the long-run covariance matrix.

$$y_t = x_t^{'}\beta + D_{it'\gamma 1} + \sum_{j=q}^{r} \Delta X_{t+j} + v_{it} \quad (6)$$

Because of the orthogonal error term cointegration equation, the DOLS estimation approach augments cointegration analysis while taking into account both the lead and lags Δ′ Xt. The aforementioned estimate implies that the long-run correlation between e_{1t} and e_{2t} may be seen by adding leads and lags (q and r) of the differenced regressors. Additionally, as was already noted, the CCR estimating approach solely relies on regression. This strategy is effective and essential for fitting the linear regression component (Park *et al.*, 2010). Therefore, the precise identification of lags and leads orders is the claimed approach's key challenge. Generally speaking, the CCR estimation can be stated as equation (7) below:

$$y_t^{*} = \beta_{pq}^{'} z_{pqt}^{*} + \mu_{pqt}^{*} \quad (7)$$

Where the aforementioned equation (7) shows that z^*_{pqt} and y^*_t are both, the stationary transformations of z_{pqt} and y_t respectively.

Results and Discussions

In the current study, descriptive statistics are first estimated to provide a summary statistics of the data being studied before moving on to empirical evaluation of the models. The average, standard deviation, and range of data series (i.e., maximum and minimum values) are all included in the descriptive statistics. The current study examined the data's normality in addition to descriptive statistics. In this regard, we used (Jarque & Bera, 1987) normality test. To define the behaviour of each chosen variable, this test combines the consideration of skewness and kurtosis. The H0 or null hypothesis for the (Jarque & Bera, 1987) test assumes that data are normaly distributed for every variable being tested. The Jarque-Bera test normal distribution shows that the excess kurtosis and skewness are both zero. The results of descriptive analysis are provided in Table 2 given below. According to summary statistics results, it is CO2 emission has the highest average and standard error values followed by GDP. It shows that in China CO2 emission surpasses the GDP. in terms of data rage, CO2 emission has the higher data range than any other series. It is also observed that environmental technologies have the lowest standard deviation, mean value and lowest data range showing that environmental technologies are the most stable variable in China.

Table 2

Summary Statics Analysis

Variables/series	Mean	Min.	Max	Std Dev.	J-B Stats
EEF	4.044	2.758	5.328	0.666	13.263***
CO2 emission	676337	3070510	10707220	2920298	23.739***
EP	66.065	45.266	87.373	32.083	16.822***
ET	8.2852	3.97	11.16	1.5886	2.7777***
GDP	5074.234	1520.027	10358.26	2934.368	2.3286***
TO	44.194	32.424	64.47	10.032	8.3328***
IV	9.333	2.464	15.050	3.041	29.732***
ICT	51.067	13.707	85.971	20.688	2.0926***
***=P<0.05					

The primary goal of the research is to study the long-term relationships between the sries under consideration. The unit root test testing provides crucial details on the order of the integration of the variables for purposes of employing the strategies to develop a long-term association. In order to analyze the integration aspects, two conventional root tests—the ADF and Philips-Perron (PP) tests—are used. The results of the both tests are presented in Table 3. The unit root issue is apparent in all series at the level before they become stationary after the first difference.

Table 3

PP and ADF Tests

	ADF Test		**PP Test**	
level	**I**	**I and T**	**I**	**I and T**
EEF	-0.332	-3.042	-2.341	-2.834
CO2	-0.433	-1.354	-1.164	-1.735
GDP	-4.645	-3.037	-4.085	-3.634
TO	-3.145	-3. 024	-5.945	-3.857
ET	-1.734	-2.746	-3.657	-2.654
EP	-2.643	-4.775	-4.087	-4.776
IV	-1.098	-3.840	-3.065	-3.923
ICT	-0.723	-1.224	-6.987	-6.985
first difference				
EEF	-3.322***	-3.446***	-3.743***	-3.532**
CO2	-2.154***	-4.946***	-3.243***	-2.134***
GDP	-4.345***	-3.456***	-3.465***	-4.754***
TO	-3.134***	-3.145***	-3.657***	-2.100***
ET	-4.546***	-3.767***	-4.456***	-3.850***
EP	-3.456***	-3.453***	-2.299***	-3.789***
IV	-1.554***	-2.678***	-3.451***	-2.499***
ICT	-2.432***	-3.484***	-4.056***	-0.381***

**** indicate 1 percent significance level respectively. I= Intercept and T= Trend*

After determining if the data is stationary, we examine the cointegration relationship among the variables of study. For this we applied Johansen Co-integration approach. The results for both models show that there is at least one cointegration equation that establishes the cointegration of the variables studied in both models.

Table 4

Johansen Cointegration Test Findings

Cointegrating equations	**Model 1 EEF = ICT, TO , GDP, EP, IV**		**Model 2 CO2 = ICT, ET, GDP, TO, IV**	
	Trace	**Max Eigen values**	**Trace**	**Max Eigen values**
None	36.946	42.645	76.953**	16.465***
	(0.346)	(0.245)	(0.043)	(0.026)
At most 1	78.134***	18.089***	16.927**	24.753***
	(0.034)	(0.031)	(0.076)	(0.014)
At most 2	12.863***	23.135***	38.775	26.574
	(0.034)	(0.056)	(0.865)	(0.256)
At most 3	21.834	12.436	12.394	13.823
	(0.833)	(0.384)	(0.753)	(0.644)
At most 4	0.557	0.637	11.010	44.014
	(0.0983)	(0.854)	(0.938)	(0.524)

Examining the cointegration connection between the variables enables us to examine at the unique long-term effects of each variable on Chinese energy efficiency and environmental sustainablity. For this purpose, we applied DOLS FMOLS, and CCR regression techniques on both models. The findings for model 1 are shown in Table 5. According to the results, all of the variables have significant effect on energy efficiency.

Table 5

Findings of DOLS, FMOLS and CCR for Model 1

Series	**F-MOLS**		**D-OLS**		**CCR**	
	Coefficients	**Prob value**	**Coefficients**	**Prob value**	**Coefficients**	**Prob value**
ICT	-1.283**	0.005	-1.154**	0.032	-1.876***	0.006
TO	-0.239***	-0.044	-0.147***	0.000	-0.986***	0.000
EP	-0.144***	0.005	-0.789***	0.000	-0.243***	0.001
IV	1.908***	0.000	0.328***	0.000	0.743***	0.008
GDP	-0.872	0.003	-1.665**	0.075	-0.432***	0.007
C	2.345***	0.000	2.678**	0.000	3.454**	0.005
R^2 value	0.746		0.749		0.766	
Adjusted R^2 value	0.734		0.737		0.752	

First of all, the empirical findings indicate that ICT influence energy intensity negatively i.e, ICT has positive contribution in increasing energy efficiency in China. For each unit rise in ICT infrastructure, we observe that energy intensity reduces or (energy efficiency increases) by 1.15 units, 1.28 units and 1.87 units in DOLS, FMOLS and CCR regression respectively. this mechanism is also observed by several previous studies including those for China by (Bildirici *et al.*, 2022), (Wang & Han, 2016), (Zhou, Zhou, & Wang, 2018), (Wen et al., 2022). The finding is justifiable because due to its ability to replace physical processes and streamline the industrial process, ICT lowers energy intensity and increases energy efficiency.

Second, the coefficient for energy prices is negative showing that increase in energy prices reduce energy intensity and promote energy efficiency. In terms of coefficients, there is an increase of 0.14 units, 0.78 units and 0.24 units in DOLS, FMOLS and in CCR in EEF if energy prices rise by 1 unit. Thus we can conclude that rising energy prices are associated with increased energy efficiency on account for the fact that rising energy prices motivate the economies or consumers to have more investment in those products that are more energy efficient rather than facing an increase in prices of energy. it definitely helps in improving energy efficiency as also evident by (Hang & Tu, 2007), (Verbic *et al.*, 2017; C. Yuan, Liu, & Wu, 2010) (Adom, 2015) and (Fitriyanto & Iskandar, 2019) from earlier studies.

Third, we found that coefficient for trade openness variable is highly significant and negative in all three specifications. For each percent increase in trade openness, energy efficiency improves by 0.23, 0.18 and 0.93 units in FMOLS, DOLS and CCR respectively. Thus the findings conclude that trade promotes the adoption of energy-efficient and energy saving technology. The ability of economies to absorb the transfer of advanced energy management technology and knowledge from abroad may be made possible by increased international trade. As a result of the adoption of more advanced technologies for energy generation, processing, and distribution, as well as the benefits of economies of scale and resource allocation from trade openness, energy use will decrease. The findings of (Pan *et al.*, 2019), (Murshed, 2020), (S. Chen *et al.*, 2022) strongly favour our results but the findings of (Kyophilavong, Shahbaz, Anwar, & Masood, 2015) and (Adom, 2015) are in sharp contrast with us.

Table 5 further shows that lowering energy efficiency levels are related to increased GDP shares from the industrial sector in terms of industry value added. Because industrial production always needs more resources, such as electricity, than the service sector does, this outcome makes sense. As a consequence, industrial production frequently uses more energy than the service industry. From earlier researches, (Sineviciene *et al.*, 2017), (Filipovic *et al.*, 2015) and (Sadorsky, 2013), (Rudenko & Tanasov, 2022). Energy efficiency is reduced by 1.90, 0.32 and 0.74 units in FMOLS, DOLS and CCR for every unit growth in industry value added in China.

The regression findings also show that energy efficiency increases along with economic growth. Energy efficiency improves by 0.87 units, 1.66 units and 0.43 units in FMOLS, DOLS and CCR respectively. Two aspects provide evidence that economic growth impacts energy efficiency positively; One the one hand, higher income might affect energy-intensive lifestyles, which results in lower energy intensity. On the other side, it might be because people in those nations are starting to embrace energy-saving devices as a result of their greater awareness of environmental issues and climate change (Bashir *et al.*, 2020). The implementation and use of energy efficient technology and procedures and improved energy resource management may be made possible by economic growth, both of which would reduce the energy intensity. The similar mechanism is also observed by (Metcalf, 2008), (Rudenko & Tanasov, 2022) (Bilgili *et al.*, 2017) (Belloumi & Alshehry, 2016) (Fitriyanto & Iskandar, 2019; Jain & Goswami, 2021) from previous studies.

After completing estimations for Model 1, now we proceed towards estimations for Model 2. Table 6 below reports the results for Model 2

Table 6

Findings of DOLS, FMOLS and CCR for Model 2

Series	**F-MOLS**		**D-OLS**		**CCR**	
	Coefficient	P-value	Coefficient	P-value	Coefficient	P-value
ICT	-0.944**	0.000	-0.543**	0.008	-0.759***	0.000
TO	0.347***	0.008	0.449***	0.000	0.666***	0.000
ET	-0.932***	0.000	-0.843***	0.000	-0.465***	0.000
IV	2.005***	0.000	1.245***	0.000	1.512***	0.000
GDP	0.714***	0.044	0.454**	0.050	0.347***	0.006
C	0.352	0.359	1.745	0.467	4.554	0.105
R^2	0.888		0.890		0.796	
Adjusted R^2	0.876		0.881		0.781	

Table 6 clearly shows that the coefficient of ICT for China using three estimating methodologies is statistically significant (FMOLS, DOLS and CCR). A unit rise in ICT leads to a reduction of 0.99 units 0.54 units and 0.75 units in CCR, DOLS and FMOLS respectively. If ICT adoption boosts production efficiency, environmental sustainability can indeed be sustained even while a country's output rises (Ozcan & Apergis, 2018). When combined, the production, inputs, and technology effects outweigh the scale effect of digitalization, the negative impact of digitalization on CO2 emissions can be seen Higon et al. (2017). ICT thereby helps China's ecology by reducing CO2 emissions and improving environmental quality. It also implies that ICT possesses the ability to separate growth from pollution or environmental degradation. The findings of (Khan *et al.*, 2020), (Majeed, 2018), (Hilty *et al.*, 2006), (Alatas, 2021), and (Ahmed *et al.*, 2021) are in line with our findings supporting that ICT sector has the favourable implications for environmental sustainability.

According to Table 6, China's GDP has significant and positive effect on carbon dioxide emissions. There is an increase of 0.71 units, 0.45 units and 0.34 units in FMOLS, DOLS and CCR respectively for a unit increase in GDP. the finding justifies that GDP measures a country's capacity to generate more products and services, but it also speeds up CO2 emissions and degrades the environment. The scale effect, which demonstrates how more energy-intensive and environmentally harmful emissions result from larger-scale economic activity, can be used to explain it. Additionally this conclusion may indicate that increased industrial activity, which increases the consumption of fossil fuels and CO2 emissions, makes it easier to produce more goods. It implies that the expansion of the industrial sector could have a substantial negative environmental impact owing to environmental pollution. The overall notion that economic growth has a detrimental effect on environmental quality is abundantly supported by previous studies including (Abbasi *et al.*, 2022; Adedoyin *et al.*, 2020; Mohsin *et al.*, 2020; Saleem *et al*., 2020). These results imply that GDP causes environmental deterioration.

The findings indicate that environmental technologies exert negative impact on emissions in China. There is decline of 0.93, 084, 0.46 units in FMOLS, DOLS and CCR respectively because of a unit increase in environmental technologies. It claims that the use of ecologically friendly and effective technologies reduces pollution and improves environmental quality. It shows that all environmental protection (detrimental material release prevention), waste collection, green infrastructure (developed strategies of production), and mitigation technology strategies affect environment in positive way. These technologies may even change the production structure to use renewable power sources and reduce CO2 emissions. Additionally, the increased focus on Research & development activities by government and business to produce capital assets that are environmentally friendly improves the effectiveness of energy-efficient industrial equipment. The findings of the study are supported by (Fethi & Rahuma, 2020), (Pofoura *et al.*, 2021), (Jun *et al*., 2022) and (Hanif *et al*., 2022) from previous studies

Table 6 also reports that trade openness impact environmental quality negatively in China. There is an increase of 0.34 units, 0.44 units and 0.66 units in DOLS, FMOLS, and CCR respectively for a unit increase in trade openness. This finding is supported by the pollution haven hypothesis, that holds that enhanced trade openness encourages ecological damage because rising income levels increase demand for a clean environment and lead dirty corporations from developed economies to seek out regions with less stringent environmental regulations. Due to the lack of substantial environmental regulations in the majority of developing Asian nations such as China, firms from advanced economies with stricter environmental standards relocate their factories and facilities to these less developed nations. Thus, the host economies with low ecological rules and regulations become environmentally dirtier with trade openness. Additionally, it is true that developing nations place more of an emphasis on conventional energy sources, which leads to larger emissions from increased manufacturing and human activity as a result of trade liberalization. (Bernard & Mandal, 2016), (Akhayere *et al.*, 2022), (Nepal *et al.*, 2021), and (Tachie *et al*., 2020) support our finding that trade openness causes the deterioration of environment. Last the impact of industrial value added is also reported in Table 6. The findings indicate that industrial value added deteriorates the environmental quality in China in three specifications. The finding justifies that increased industrialization process is associated with rising energy consumption mainly drived from fossil fuel sources that cause CO2 emission to raise. The findings of (Liu & Bae, 2018; Mentel *et al.*, 2022; Shahbaz *et al.*, 2014) from previous literature support our findings. In coefficient terms, 2.0, 1.5 and 1.2 units of CO2 emissions decline in FMOLS, DOLS, CCR for one unit rise in industrialization.

Conclusion and Policy Recommendations

The present study investigates the effect of digital technologies on energy efficiency and environmental sustainability in China over 1995-2020 period. To fulfill the study objective, the study formulates two separate models: Model 1 for energy efficiency and Model 2 for environmental sustainability. To estimate the objectives empirically, we applied three time series approaches namely FMOLS, CCR and DOLS. The findings show that ICT has negative effect on energy intensity (hence positive on energy efficiency) and CO2 emission in all the three specifications. Thus the study concluded that ICT has beneficial implications in terms of energy efficiency and environmental quality for China.

These findings have some worthy policy recommendations for China. The Chinese government is already aware of how ICT may help reducing energy intensity. The conclusions of the research suggest that to achieve a reduction in energy intensity, policy-makers should give the ICT industry the attention it deserves. Therefore, we recommend that the Chinese government encourages the shift from traditional industry that is manufacturing to one that is service-oriented by using ICT. Additionally, in order to attract investments, the software and information service sectors should be chosen above the manufacturing of hardware. Technology tools should be expanded into additional industries, such as the manufacturing sector for monitoring and production optimization, and the transportation sector for intelligent management and locating.

For positive contribution of ICT sector in environmental sustainability, The Chinese government can lower their carbon intensity levels by using advanced ICT technologies. Smart TVs, cellphones, energy-efficient appliances, and other ICT advancements are significant post-industrial innovations with the potential to reduce CO2 emissions. Access to the internet should be made easier and additional Internet infrastructure should be constructed, especially in rural and distant places without an existing Internet connection. Therefore, having access to the Internet will make it easier for people to do more shopping online, attend video conferences, and work from home rather than traveling. Because less energy is used, emissions will be minimized as a result.

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