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Environmental Impact of ICT on Disaggregated Energy Consumption in China: A Threshold Regression Analysis

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Abstract: Due to resource scarcity, high energy demand, and environmental degradation, China's rapid economic growth over the past three decades has been accompanied by certain serious issues that require quick attention. The excessive use of fossil fuels worsens the ecosystem and raises the level of carbon in the atmosphere. However, the use of ICT has affected the behavior of energy use in various sectors differently. Although ICT-induced activities, on one hand, may affect the environment positively by reducing energy consumption, on the other hand, they may affect the environment adversely by causing an energy rebound effect. Therefore, this study aims to investigate the nonlinear impact of ICT on the environmental effects of energy consumption in the residential, transport, and industrial sectors in China. The study used threshold regression for empirical analysis by employing data for the period from 1990 to 2021. ICT is used as a threshold variable, while energy consumption in the residential, industrial, and transport sectors is used as a regime-dependent variable. Based on the findings, we deduce that the use of ICT asymmetrically affects sectoral energy consumption and the empirical result varies across sectors. Based on the results, we recommend that the possibility of rebound effects should be given more attention in the development of policies regarding the digitalization of the sectors.

Keywords: environment; ICT; CO_2 emission; energy consumption; threshold regression; N-shaped EKC

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1. Introduction

The high-speed economic expansion in China in the last few decades has been accompanied by some severe problems, including resource scarcity, high energy demand, and environmental damage that needs an immediate solution. As a direct input into the industry and through the numerous services it offers, the natural environment is crucial to every economy. Minerals and fossil fuels are examples of environmental resources that directly assist in the production of commodities and services, while, on the other hand, it causes an increase in the carbon level in the air and degrades the ecosystem. The extent of environmental stress and degradation has become the topic of debate at all economic and development platforms, and it is now obvious that the current level of the influence of human activities on the environment cannot be sustained into the future without causing unacceptable harm to life on our planet. Future generations will be swamped by environmental deterioration and social collapse if we fail to transform our self-destructing economy into one that is environmentally sustainable. However, the most effective means of achieving sustainable development is to restrict economic and population expansion while simultaneously encouraging technological advancement to lessen the environmental impact of human activities.

A report by NOAA (2021) [1] revealed that the average rise in the ocean and land temperature since 1880 has been 0.07 degrees Celsius per decade. The pace of temperature increases since 1981 has been 0.18 degrees Celsius on average, which is more than twice as in prior decades. Extreme weather results in heat waves, floods, and droughts, as well as water system disruptions, which are all caused by global warming [2]. According to Pörtner et al. (2022) [3], global warming will exceed 1.5 °C in the near future, several climatic disasters will become unavoidable, and humanity and ecosystems will face numerous risks as a result. People who live in areas that are extremely affected by climate change number around 3.3 to 3.6 billion. Numerous species are threatened by climate change. Actions such as controls in socioeconomic growth, susceptibility to exposure, and adaptation are required to keep rising temperatures below 1.5 °C, which will significantly cut down on the expected losses and harm from global warming to both ecosystems and humans. The main factor which is responsible for the rise in temperature and climate change is CO_2 emission. Exposure to CO_2 emissions is also linked to several health issues, many of which are inflammatory, such as respiratory acidosis. In addition, it can modify the makeup of the bones and kidneys, cause physiological and behavioral abnormalities, and also cause oxidative alterations [4]. Reduction in CO_2 emissions will surmount these health challenges.

Since China acceded to the WTO, its economy has rapidly grown, and significant changes have been made to its industrial structure. The major goals of economic reforms in China are to change and modernize the industrial structure as the country goes through a critical phase of economic transition. In Asia, Japan is the only developed nation as, per the report WESP (2022) [5], China is still a developing economy even though it has the second-largest economy in the world. There are 4.71 billion people living in Asia, making up around 59.76% of the world's population, of which only China accounts for 18.47% [6]. It is difficult for governments of Asian countries to meet the energy needs of the continent's enormous population virtually, but it is also a worldwide issue in terms of CO_2 emissions. China is the country with the highest CO_2 emissions, contributing 33% of the world's CO_2 emissions in 2020 (11.9 billion tonnes) [7]. According to Dale (2021) [8], only China accounted for 59 percent of Asia's CO_2 emissions, so serious action needs to be taken by considering different ways. Wang et al. (2020) [9] highlighted that China invested heavily and used a lot of fossil fuel energy until 2014. However, by the end of the same year, in an effort to move toward a greener growth path, it stopped increasing its use of fossil fuels and increased its use of renewable energy sources. Sustainable investment in the energy sector ensures sustainable development as well as mitigating pronounced levels of air pollution in order to alleviate both air pollution and the sustainability of growth [10]. Figure 1 shows an upward trend of per capita carbon emissions in China. The graph shows a drastic increase in carbon emissions after 2001.

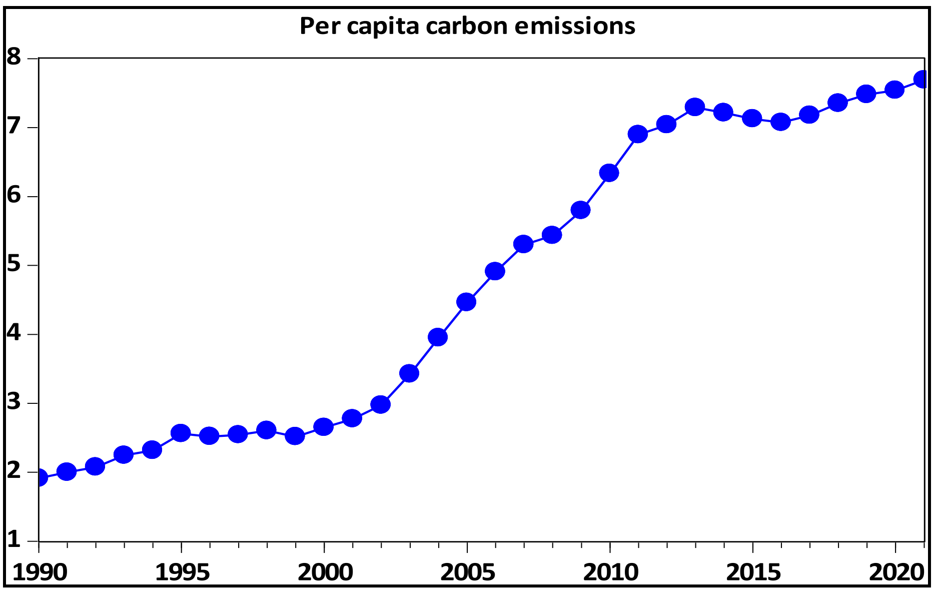

Figure 1. Per capita carbon emission in China.

Over the past twenty years, information and communication technology has grown rapidly. Previous empirical studies suggested that one way to boost efficiency while lowering energy usage is to employ information technology to support economic growth. Utilizing information and communication technology to cut back on commuting will also help reduce CO_2 emissions and ultimately pollution. The internet may increase energy efficiency, and the decline in energy consumption has a favorable impact on environmental quality [11]. The usage of ICT may increase production effectiveness and decrease material product consumption, which in turn lowers energy demand and lessens the environmental load. The ICT industry itself consumes 4–6% of all the power produced worldwide in 2020. According to Ferreboeuf et al. (2019) [12], the carbon footprint associated with digital activities accounts for around 4% of global emissions, or 2 gigatonnes of CO_2, out of which terminals account for 66% of digital emissions, followed by networks (19%) and data centers (15%). According to Lorincz et al. (2019) [13], by 2030, just 1.97 percent of the world's carbon emissions will come from the ICT sector. Instead, the broad use of ICT technology will make it possible for other industries to drastically cut their carbon emissions. ICT technologies can decouple economic development from emissions increase by 2030 by reducing global CO_2 emissions by 20%, which is ten times the carbon emissions of the ICT sector as a whole (Telecom lead, 28 February 2022 "MWC 2022: ICT is not a contributor to carbon footprint, but an enabler of carbon handprints, says Huawei").

China is undertaking serious investments in ICT, which results in boosting the country's economy by generating income, opening up employment opportunities, and exporting goods. China's spending on ICT infrastructure increased by 21.8 percent annually from 1978 to 2018, which is near twice the country's spending on non-ICT infrastructure. Comparatively, China's service sector uses ICT more than the industrial sector [14]. Transition in ICT will not only impact the economic factors but also help the ecological aspect through resource efficiency and renewable energy. Webb (2008) [15] asserts that the environmental benefits of ICT services may outweigh their negative effects on greenhouse gas emissions. Internet penetration in China reached 74.4 percent by June 2022, with 1.05 billion people using the internet. The Chinese government's interest in the potential of ICT to accelerate economic growth and alter industrial methods took place as the country entered a period of an economic "New Normal." In order to integrate ICT with the energy system, the national energy administration sponsored 55 "Internet plus" smart energy demonstration projects in 2017 [16]. Figure 2 shows the number of internet users in millions over time as an indicator of ICT development in China. China had its first web server in 1994, and by 1997 there were 620,000 internet users. The figure shows that the number of internet users increased drastically after the year 2005. China's household broadband penetration was just 39% in 2013, and in 2021, there were more than 1.02 billion internet users in China, which shows the fast expansion of ICT in the Chinese economy.

Understanding ICT's environmental effects is essential for addressing climate change concerns. Global economies, communities, and the environment have all seen a significant transformation as a result of ICT. According to the study of Park et al. (2018) [17], the use of the internet primarily has a huge impact on increasing energy efficiency and thus reducing the environmental pollution. Ulucak and Khan's (2020) [18] investigation explored that ICT has three different environmental effects: use effect, substitution effect, and cost effect. During the usage effect, production, distribution, and installation of ICT equipment occurs and energy consumption increases, while, on the other hand, e-waste creation and ICT equipment emit carbon and affect the environment adversely. The substitution effect prevails when ICT improves the effectiveness of existing mechanisms as well as energy production and usage patterns and results in decarbonization. The cost effect occurs when demand for products and services rises as a result of price declines due to ICT-induced technological progress. The cost effect speeds up carbon emissions and thus affects the environment negatively.

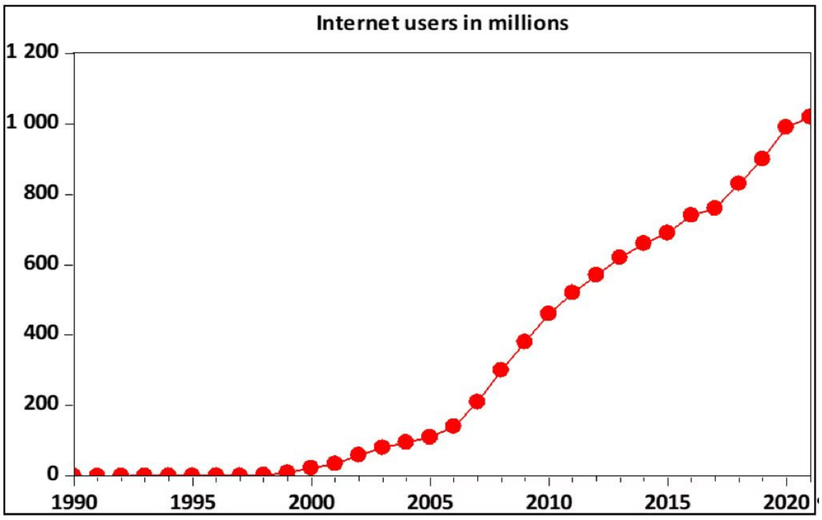

Figure 2. Internet users in millions in China.

Regarding how ICT affects energy use and the environment, there is a disagreement in the literature. The impact of ICT on energy use in developing nations has only been briefly examined by researchers. To the best of our knowledge, the literature does not provide empirical evidence on the asymmetric environmental effect of ICT on sector-wise energy consumption in China. This study attempts to investigate the environmental effect of ICT on energy use in the industrial, residential, and industrial sectors of China and assesses the threshold effect of ICT on environmental quality. The empirical evidence on the association between ICT, energy consumption, and the environment in China will help policymakers to establish environmentally sustainable strategies regarding the penetration of ICT in different sectors of China.

The remaining research is as follows: The section "Literature Review" examines previous literature. The third segment of this study explains the model and methodology, while the fourth part explores the results and analysis of the empirical study. The "Conclusion and policy suggestion" section summarizes the research's conclusions and makes policy suggestions in light of the findings.

2. Literature Review

Information and communication technologies (ICTs) are becoming more and more ingrained in our daily lives as the population increases. About a decade ago, there were concerns that ICT would eventually use an unsustainable portion of the total amount of energy available [19–21]. Integrated technology for driving aids for cars and transportation effectiveness are exactly sectors where "intelligent" technologies (with embedded ICT) are said to offer considerable reduction in CO_2, which is 1.5 Gt, followed by the industry of e-commerce and e-goods (0.9 Gt). Gelenbe and Caseau (2015) [22] claim that the application of ICT in the industrial and energy sectors reduces demand by 0.8 Gt. However, to understand the association between ICT and sector-wise energy use, we have divided the literature review into three main sections which explain the link between ICT and energy use in industrial, transportation, and residential sectors, which are considered more energy-consuming sectors.

2.1. Integration of ICT in Industrial Energy Consumption and Environment

Despite helping to drive economic progress, the fast expansion in industrialization has resulted in environmental contamination and negatively impacts human health. Haider et al. (2019) [23] assessed the environmental condition in India and asserted that high per capita CO_2 emissions are mostly the result of the country's soaring energy consumption, which is caused by fast industrialization and uncontrolled urbanization. The high rate of industrialization is the biggest cause of carbon emissions. The expansion of the industrial sector makes it feasible to produce more items, but doing so increases the use of fossil fuels and carbon emissions [24]. As stated by IEA (2021) [7], the industrial sector accounted for 38% (156 EJ) of the world's total final energy usage of all sectors in 2020. Despite a 1.6% fall in 2020 brought on by weaker industrial activity in several parts of the world during the COVID-19 crisis, this constitutes an average yearly rise in energy consumption of 1% from 2010 to 2019, whereas information communication and technology may help to cut down on energy use. According to Jorgenson and Vu (2016) [25], the structural changes brought about by ICT advances over the past several decades have transformed the manufacturing economy and the economic expansion has increased as a result. Ardolino et al. (2018) [26] are of the view that in the modern generation of Industry 4.0, the development and use of digital technologies have become some of the most frequently debated topics in both academic and professional circles. In the era of Industry 4.0, a collection of various intelligent and innovative technologies that realize connectivity, communication, and automation are collectively referred to as "digital technologies." Examples of these technologies include big data analytics, the Internet of Things, and cloud computing. According to Beier et al. (2018) [27] and Maddikunta et al. (2022) [28], industrial ICTs provide predictive maintenance, enhanced recycling procedures, and production that is more resource-efficient. Jiang et al. (2021) [29] also back the argument and find that the COVID-19 impact of improved ICT, including digitalization and the Internet of Things (IoT), helps the growth of green energy and the circular economy. ICT also contributes to a reduction in paperwork, which improves environmental quality. Businesses may lessen their impact on the environment by implementing ICT-focused methods, such as conferencing or networked point-of-sale systems [30–33]. In OECD nations, Schulte et al. (2016) [34] discovered analytical evidence that ICT contributed to the greater happening of energy efficiency by lowering the power consumed by 27 selected industries. Contrary to that, Zhou et al. (2018) [35] found that ICT increased the energy intensity of Chinese industries by 4.5%. Shahnazi and Dehghan Shabani (2019) [36] revealed that ICT and emission of CO_2 in the industrial sector had a bidirectional short-run causal relationship, while Shabani and Shahnazi (2019) [37] discovered that ICT increased emissions in the manufacturing sector.

2.2. Transportation Energy Consumption and Role of ICT

Because of the high pace of urbanization, there is a greater need for transportation and industrialization, which increases energy consumption and, as a result, CO_2 emissions. The transport industry is known to be responsible for around 21% of the world's emissions. Out of this, the transportation sector on roads accounts for 75%, or 15%, of all carbon dioxide emissions. Transportation emissions are made up of shipping, rail, freight, and other sources, which make up 10.6%, 1%, and 2.2% of the overall emissions, respectively [7]. Aviation makes up 11.6% of the total emissions [38]. It is evident from the reports of Conti et al. (2016) [39] that energy usage in the transportation industry is expected to increase by 1.4% per year on average, from 104 (Btu) in 2012 to 155 quadrillion Btu in 2040. Aune et al. (2017) [40] argued that information and communication technology (ICT) has the capability to reduce energy intensity in the transport industry of these countries that have high energy intensity. More use of ICT can increase the level of consumption of petroleum products in the transportation sector in the selected OECD countries, while more ICT use can decrease the intensity of the usage of petroleum products in the transportation sector in the selected OPEC countries.

The International Renewable Energy Agency (2022) [41] reports that utilizing ICT systems in the transport industry will be crucial to make the transition from traditional oil and coal automotive vehicles to contemporary hybrid technology that is fueled by comparatively cleaner fuels, thus reducing CO_2 emissions from the transport industry as a whole. ICT, energy usage, carbon pollution, and GDP in Iran's economic sectors between 2002 and 2013 were studied by Shabani and Shahnazi (2019) [37], and they discovered that ICT decreased emissions in the transport and services sectors. According to Mersky and Langer (2021) [42], ICT-based operational improvements in freight transportation in the USA can significantly lower GHG emissions. Houghton (2010) [43], Mondragon et al. (2015) [44], and Gohar and Nencioni (2021) [45] concluded that ICTs have an impact on the environment through the effects of ICTs' applications, such as intelligent transportation systems, buildings, and smart grids, and rebound through the use of more energy-efficient transportation.

According to Niyibizi and Komakech (2013) [46], ICT can help developing nations save energy and slow down climate change, and ICT in transportation can conserve energy and lessen the carbon imprint in poor nations. Zhang and Liang (2012) [47] reviewed the growth and impacts of green ICT in China and concluded that ICT significantly increases the energy efficiency of China, especially in construction, transport, agriculture, and public services. Together, ICT and renewable energy help to decrease the consumption of conventional fossil fuels and replace them. ICT can help achieve environmental goals in addition to energy goals. They contend that national-level policies should support the development of green ICT and that it is vital to launch pilot projects that demonstrate how green ICT may be used to benefit China's natural and social environment. On the other hand, the growing popularity of online education has decreased travel, which has a negative impact on CO_2 emissions. P2P, online banking, e-wallets, and other financial services supported by ICT are also examples of the benefits of ICT which have reduced traveling and decreased energy consumption in the transportation sector [48].

2.3. Residential Sector and ICT Involvement in Reduction in Energy Usage

The expectations of households using energy-related ICT have been addressed by the European Commission many times [49,50]. Although households may be encouraged to purchase more energy-efficient appliances by using ICT, not all of the predicted decreases in power use would be attributable to ICT-related effects. Houghton (2010) [43] examined that one of the main reasons that ICT has a negative influence on gross energy consumption is the enhancement of energy productivity. That is, ICT may encourage energy-efficiency improvement in domestic life through energy monitoring and management apps. In a similar vein, Bastida et al. (2019) [51] argued that it is possible to lower home final power usage by 0 to 5% as a result of ICT-based influences on consumer behavior.

By enabling customers to choose more cost-effective energy options, the transition to a low-carbon power system is projected to be aided by information and communication technology [11]. The main innovation in the ICT-energy space is the smart meter, a part of sophisticated electricity metering infrastructure that allows high-resolution (hourly or quarter-hourly) monitoring and backup of electricity data, as well as a close-to-real-time information exchange of this information to consumers and energy provider companies. Household energy management, battery system management, distributed renewable energy production management, dynamic (time-variant) power pricing, demand forecasting, and load-shifting (demand response) are all made possible by smart meter technology [52]. Using online meal ordering and purchasing as an alternative to offline consumption and home cooking might increase transportation energy use. Aebischer and Hilty's (2015) [53] views show that, in Germany, the percentage of ICT electricity is substantially greater, it was anticipated that both the residential and commercial sectors would have increased by over 25% and over 20%, respectively, and they forecasted that, in 2020, this will account for 12% of the total power consumption.

Table 1 demonstrates the chronological evolution of energy consumption, ICT, and environmental issues in China. The review of the past studies has given an insight into the need to have environmentally sustainable human activities in residential, transport, and industrial sectors because these activities result in the excessive use of energy resources, which ultimately degrades the environment. The studies have also highlighted the effect of ICT on sectoral energy demand. Some of the studies have regarded ICT as the cause of environmental degradation and the rest have concluded that ICT has a positive effect on the environment, and this difference in the conclusion is due to the asymmetric effect of ICT on energy use. Therefore, this study makes an attempt to bridge the gap by exploring the threshold level of ICT and assessing the environmental effect of ICT on sectoral energy consumption in China.

Table 1. Previous studies on sectoral energy consumption, ICT, and environment in China.

Authors'Name	Data	Methods	Findings
		Residential Sector	
Sathaye and Tyler (1991) [54]	Surveys on households in 12 cities 1989–1990	Trend analysis	According to the findings of household surveys carried out in China, the Philippines, India, Thailand, and Hong Kong, the rising consumption of commercial fuel in the residential sector is the outcome of altered patterns of household activity and livelihood.
Zhang (2004) [55]	1990–2000	Trend analysis	Findings show that, since the 1990s, China's residential sector's direct coal consumption had been declining, while the use of electricity and gases had been rising.
Zhao et al. (2012) [56]	1998–2007	LMDI Method	Findings revealed a significant structural shift toward a more energy-intensive household consumption structure as well as a significant structural shift in favor of high-quality and cleaner energy sources in China.
Cao et al. (2017) [57]	2002–2009	OLS, Ologit	It is anticipated that between 2009 and 2025, China's home electricity consumption will rise by a factor between 85% and 143%.
Qin et al. (2022) [58]	Three waves of Survey of China's Family Panel Study	Panel fixed regression, Difference-in-differences estimation	Households' electricity consumption decreases in the short run after obtaining access to the internet.
		Industrial Sector	
Price et al. (2000). [59]	1970–1995	Statistical Analysis	The results show energy efficiency has significantly increased in several areas in China since 1980.
Liu et al. (2007) [60]	1998–2005	LMDI	It is examined that, between 1998 and 2005, China's industrial sectors' carbon emissions changed significantly as a result of changes in both industrial structure and energy intensity.
Wang et al. (2010) [61]	1998–2007	LMDI	Although the structural change was found to have a minimal impact on the growth in electricity use, the technological effect, however, is to blame for a drop in electricity usage during this time.
Hu et al. (2020) [62]	2005–2015	DID method	The findings show that the carbon emission trading scheme in industrial areas of China reduces CO_2 emissions by 15.5% and energy consumption of the regulated industries by 22.8%.
Ren et al. (2021) [63]	2006–2017	OLS, Sys-GMM	The energy consumption structure and internet development are highly inversely correlated, and internet development has an impact on the energy consumption structure via economic growth, R&D spending, human capital, financial development, and industrial structure.
		Transport Sector	
He et al. (2005) [64]	1997–2002	Bottom-up model	Road transportation has steadily overtaken other modes of transportation in China. As a result, road transportation uses a lot of oil and emits a lot of CO_2.
Ji and Chen (2006) [65]	1978- 2002	Weighted mean index for exergy consumption intensity	Up until 2000, 30.5% of China's total oil consumption was accounted for by the exergy of the oil used for transportation.
Chang et al. (2013) [66]	2009	DEA model	The findings revealed that the majority of China's regions lack an eco-efficient transportation sector.
Hao et al. (2015) [67]	2000–2013	Bottom-up accounting approach	Results show that with rises of almost 1.5 times from 2010 to 2050, energy use and GHG emissions will expand quickly in the following decades.
Godil et al. (2021) [68]	1990–2018	QARDL	The use of renewable energy and technology both have a negative effect on CO_2 emissions related to transportation.

3. Methodology

3.1. Model for the Variables

This section introduces the research methodology used to examine the relationship between ICT, energy consumption, and CO_2 emissions. ICTs are anticipated to reduce CO_2 emissions by launching smart cities, smart transportation networks, innovative industrial processes, and energy efficiency improvements. Studies in the literature have determined that ICTs have an impact on environmental sustainability that is either beneficial or detrimental [69]. The studies by Han et al. (2016) [70] concluded that there exists an asymmetric relation between ICT and energy use in China. Additionally, ICT gives employees more free time, lowers consumer prices, boosts productivity, and increases company profits. However, these benefits come at the cost of higher aggregate consumption and increased CO_2 emissions, a phenomenon known as the rebound effect, which cancels out the initial benefit of ICT to the environment. Thus, following the study of Han et al. (2016), this study examines the asymmetric environmental effect of ICT on disaggregated energy consumption in China using the threshold model. The flowchart of the relationship between ICT, energy consumption, and carbon emissions is given in Figure 3. The figure explains that ICT affects the energy consumption of the residential, transport, and industrial sectors, which ultimately affects the environmental quality.

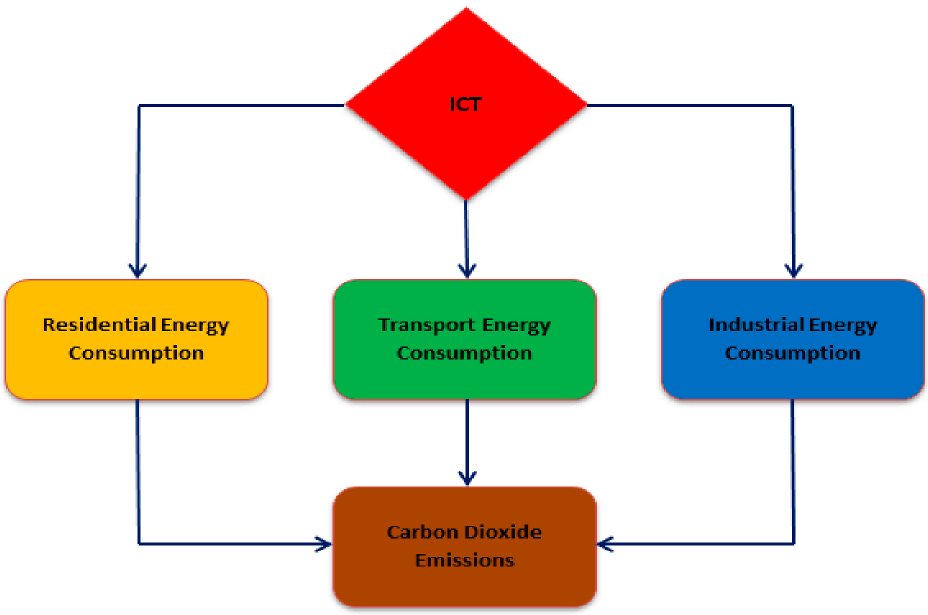

Figure 3. Relationship between ICT, energy consumption, and environment (authors' illustration).

The threshold regression model introduced by Hansen (2000) [71] is a method that is used in particular to look at nonlinearity in relationships. Indeed, the threshold regression model captures the nonlinear relationship between the threshold variable, regime-dependent variables, and their effect on the dependent variables [72]. Li et al. (2021) [73] also used the threshold model to analyze the environmental effect of energy intensity on renewable energy consumption in China. Since ICT is expected to affect energy consumption nonlinearly, there must exist a threshold level of ICT after which the relationship between ICT and energy consumption alters. Utilizing this paradigm, we were able to estimate the threshold level of the ICT that divides the relationship between energy consumption in different sectors of the economy and carbon emissions into two regimes, that is, before and after the threshold level. Thus, this study contributes to the existing literature on the application of threshold regression analysis on time series data since most of the threshold regression in the literature was conducted on panel data.

Once the stationarity of the series has been confirmed by the KPSS test (Kwiatkowski et al., 1992) [74] and the ADF-GLS test (Elliott et al., 1996) [75], we begin by taking into account the following variables as we develop our model: y_t, q_t, r_t, and x_t, where y_t stands for the dependent variable, q_t is the threshold variable, r_t is the regime-dependent variable, and x_t is the vector of control variables.

The relationship is split into two regimes by the threshold variable; hence, the following model can be used to describe the relationship:

$$y_t = r_t\alpha_1^1 + e_t,\ q_t \le \theta \tag{1}$$

$$y_t = r_t\alpha_1^2 + e_t,\ q_t > \theta \tag{2}$$

In the above equations, θ is used to indicate the threshold value. The model can be shown as follows when an indicator function I (q_t) is introduced:

$$y_t = r_t\alpha_1^1\ I(q_t \le \theta) + r_t\alpha_1^2 I\ (q_t > \theta) + e_t \tag{3}$$

However, after including the vector of control variables, the model takes the following form:

$$y_t = r_t\alpha_1^1\ I(q_t \le \theta) + r_t\alpha_1^2 I\ (q_t > \theta) + x_t\ \alpha_2 + e_t \tag{4}$$

This study uses the endogenous threshold determination algorithm described by Hansen (2000) to derive the threshold value and estimate the parameters of Equation (4). The goal of this process is to identify a particular threshold value that minimizes the sum of the squared residuals.

To conduct the empirical analysis, we estimate the threshold effect of ICT on the relationship between disaggregated energy consumption and carbon emissions. Thus, the model can be written as follows:

$$CE_t = \alpha_1 + \alpha_2 Pop_t + \alpha_3 GDP_t + \alpha_4 GDP_t^2 + \alpha_5 GDP_t^3 + \alpha_6 E_t(ICT_t \le\ \theta) + \alpha_7 E_t(ICT_t > \theta) +\ e_t \tag{5}$$

In Equation (5), CE is carbon emissions, Pop is the total population, GDP is GDP at a constant price, and E is energy consumption. θ is used to denote the threshold level of ICT and it takes the form of a binary value of 1 or 0, denoting values that are either above or below the threshold level, accordingly. Following the study of Allard et al. (2018) [76], we introduce an N-type link between environmental degradation and economic activities because it makes the carbon-economy nexus more adaptable. In order to test the N-shaped EKC hypothesis, we take into account the squared and cubic value of GDP, which helps in measuring N-shaped phenomena in the model. The N-shaped EKC hypothesis is true if the estimated coefficient of the linear term of GDP is positive and the squared value of GDP has a negative effect and the cubic term has a positive effect on environmental degradation. However, if the linear term attains a negative sign, the quadratic a positive sign, and the cubic term attains a negative sign, then we will have an inverted-N shaped EKC. Additionally, this study also intends to assess the threshold effect of technology on disaggregated energy use, and, for this purpose, it takes into account the residential, industrial, and transportation sectors. Thus, the following form of Equation (2) can be used:

$$\begin{aligned} CE_t = \alpha_1 + \alpha_2 Pop_t + \alpha_3 GDP_t + \alpha_4 GDP_t^2 + \alpha_5 GDP_t^3 + \alpha_6 RE_t(ICT_t \le\ \theta) + \alpha_7 RE_t(ICT_t > \theta) + \alpha_8 INE_t(ICT_t \\ \le\ \theta) + \alpha_9 INE_t(ICT_t > \theta) +\ \alpha_{10} TE_t(ICT_t \le\ \theta) + \alpha_{11} TE_t(ICT_t > \theta) +\ e_t \end{aligned} \tag{6}$$

where RE denotes energy usage in the residential sector, INE denotes energy use in the industrial sector, and TE denotes energy use in the transport sector. The logarithmic form of each variable was employed in the aforementioned model.

3.2. Data

In order to proceed with the empirical analysis, this study uses time series data from China for the period 1990–2021. The dependent variable is carbon emissions in kt. Since this study aims to investigate how the level of ICT before and after the threshold level affects the consumption of energy in different sectors, that is the transport, residential, and industrial sectors of the Chinese economy, we have used ICT as a threshold variable. Given that the data on ICT are not readily available, many studies have used internet users as a proxy variable for ICT [77–79]. We have also used the number of internet users as a proxy for ICT and the data on internet users have been gathered from the WDI database. The regime-dependent variables of this study are energy consumption in the industrial sector, energy consumption in the residential sector, and energy consumption in the transportation sector, and data on these variables are collected from the IEA database. Other than the threshold and regime-dependent variables, the model of this study includes control variables, that is, GDP and population, while the data on both the control variables are collected from the WDI database.

4. Results and Discussion

The statistical overview of the variables is shown in Table 2, which contains the average value, minimum and maximum values, and standard deviation as a measure of dispersion. Skewness and kurtosis are used to assess if the variables are normally distributed or not.

Table 2. Statistical Summary.

Variable	Mean	Stdev.	Min	Max	Skew	Kurt
CO_2	6.15e+06	3.17e+06	2.20e+06	1.10e+07	0.194	1.318
ICT	3.54e+08	3.58e+08	0	1.08e+09	0.560	1.874
RE	1.25e+07	9.87e+05	1.14e+07	1.48e+07	1.378	3.670
INE	2.62e+07	1.36e+07	9.85e+06	4.37e+07	0.119	1.247
TE	6.54e+06	4.37e+06	1.32e+06	1.38e+07	0.381	1.690
GDP	4.89e+12	4.87e+12	3.6e+11	1.5e+13	0.788	2.139
Pop	1.3e+09	8.3e+07	1.10e+09	1.41e+09	−0.352	2.080

According to the statistical summary, the average carbon emission in China during the period of 1990–2021 was 6.15e+06 kt with a standard deviation of 3.17e+06. The value of skewness was 0.194, which is closer to zero, showing symmetry in the distribution, while the value of kurtosis was lower than 3. The average value of ICT was recorded as 3.54e+08 with a standard deviation of 3.58e+08. The value of skewness was 0.56, whereas the value of kurtosis was 1.874, which shows a deviation from the standard normal distribution. The average values of the regime-dependent variables RE, INE, and TE were 1.25e+07, 2.62e+07, and 6.54e+06, respectively. The values of skewness and kurtosis show that these variables are not normally distributed. The average population in China during the period under study was 1.3e+09 with a standard deviation of 8.3e+07, while the values of skewness and kurtosis show that distribution is slightly normal, and the average GDP was 4.89e+12 with a standard deviation of 4.87e+12.

The correlation analysis is given in Table 3. Correlation measures the degree of linear association between variables. The correlation coefficient values show that CO_2 emissions are positively related to other variables of the model, and the correlation of carbon emissions with industrial energy consumption, transport energy, GDP, and population are relatively strong. ICT is positively related to all variables except population, while the value of the coefficient shows a weak relationship between them. ICT is strongly correlated with GDP, while its relationship with energy consumption is weak, which indicates the hat relationship between ICT and energy consumption is nonlinear. Residential energy consumption is uncorrelated with industrial energy consumption, GDP, and transport energy consumption, while it is highly correlated with population. Industrial energy consumption is found to be positively related to transport energy consumption as the industrial activities require mobility of labor and raw material and thus affect transportation. Industrial energy consumption is also positively related to GDP and population. Transportation energy consumption is positively related to GDP and population. GDP and population are also correlated because an increase in the population affects aggregate demand, which stimulates economic activities. Table 4 reports the VIF values for the regressors. The lower value of VIF is 1, and there is no cap on its upper value. The rule of thumb for the low-to-moderate level of correlation is the value of VIF between 1 and 5. Since the VIF value for none of the variables exceeds 5, we conclude that a severe problem of multicollinearity does not exist.

Table 3. Correlation Analysis.

Variable	CO_2	ICT	RE	INE	TE	GDP	Pop
CO_2	1.000						
ICT	0.461	1.000					
RE	0.543	0.327	1.000				
INE	0.859	0.263	0.483	1.000			
TE	0.736	0.468	0.228	0.722	1.000		
GDP	0.632	0.732	0.161	0.800	0.616	1.000	
Pop	0.823	−0.164	0.779	0.651	0.711	0.559	1.000

Table 4. VIF values.

Variable	ICT	RE	INE	TE	GDP	Pop
VIF	5.03	3.56	4.33	2.09	4.86	5.09

Before moving to the estimation of the parameters of the model, the stationarity of the series under examination is first tested because we are dealing with time series data. We applied KPSS and ADF-GLS tests on the logged series to examine stationarity. Table 5 lists the results of the unit root tests. The KPSS test's results indicate that the null hypothesis of no unit root was accepted, however, the ADF-GLS test indicated that the null hypothesis of non-stationarity is rejected. Thus, based on the unit test results, we conclude that the variables are stationary at the level.

Table 5. Result of unit root tests.

Variables	ADF-GLS	KPSS
$lnCO_2$	−1.679 *	1.524
lnICT	−2.488 *	1.116
lnRE	−4.619 ***	0.824
lnINE	−2.677 **	1.107
lnTE	−1.713 *	1.492
lnGDP	−2.521 **	1.100
$lnGDP^2$	−3.823 ***	0.991
$lnGDP^3$	−2.531 **	1.248
lnPop	−2.119 *	1.139

Note: *, **, and *** indicate the significance level at 1, 5, and 10 percent, respectively.

The result of threshold regression is reported in Table 6. Results indicate that an increase in economic growth affects carbon emissions negatively and the value is significant at a 1 percent level of significance, which implies that environmental quality improves with the increase in economic expansion initially. This means that, over time, the benefits of economic growth for mitigating CO_2 emissions will be achieved. The coefficient of the quadratic term is positive and significant, implying degradation in the environmental quality, whereas the cubic term is carrying a negative sign, thus we have found an inverted N-shaped EKC for the Chinese economy. Our finding is in line with the result of Li et al. (2019) [80], who explained that the N-shape of EKC is congruent with the stages of China's economic development. Before modernization and industrialization, carbon emissions declined with economic growth; after that, with the increase in industrialization and urbanization, the Chinese economy moved towards a low to moderate economic expansion, which has resulted in an increase in carbon emissions and created other environmental issues in the country, and kept rising until the economy reached a turning point; finally, as the growth of GDP rises, carbon emissions decline and lead the economy towards sustainability. Since it seems improbable that the turning point will be achieved shortly, environmental regulations are necessary to counteract unexpected environmental impacts and hasten the advent of the turning point for the economy.

Table 6. Effect of ICT on the Link between Energy Use and CO_2 emissions.

Variable	Coefficient	z-Value	Prob.
$lnGDP_t$	−5.012 ***	−3.53	0.000
$lnGDP_t^2$	0.893 ***	3.24	0.002
$lnGDP_t^3$	−0.0025 **	−2.59	0.012
$lnPop_t$	2.805 **	2.34	0.019
$lnRE_t(lnICT_t \leq \gamma_1)$	0.673 *	1.61	0.083
$lnRE_t(lnICT_t > \gamma_2)$	0.807 **	2.16	0.031
$lnTE_t(lnICT_t \leq \gamma_1)$	1.273 ***	3.44	0.001
$lnTE_t(lnICT_t > \gamma_2)$	0.785 **	2.42	0.015
$lnINE_{it}(lnICT_t \leq \gamma_1)$	1.439 ***	12.90	0.000
$lnINE_t(lnICT_t > \gamma_2)$	2.269 ***	8.30	0.000
Constant	5.183	1.10	0.271
Threshold: 4.818 SSR = 0.0040			

Note: *, **, and *** indicate the significance level at 1, 5, and 10 percent, respectively.

The coefficient of the population is positive and significant at a 5 percent level of significance, suggesting that with every 1 percent increase in the population, carbon emissions will increase by 2.805 percent. China's fertility rate has been steadily declining since 1995 as a result of the family planning efforts that have been made and the policy that has been continuously implemented since then. However, despite the population structure taking a smaller and smaller share of the global population each year, China's population was still growing. There is now less room for people to live because of the deterioration of the ecological environment and changes in how land is used. The amount of carbon dioxide produced by energy use was steadily rising along with the rising demand for energy from a huge number of people [81]. As a result, China's population continues to be the primary driver of its carbon emissions. It is likely that China's population, natural resources, and environment will continue to face significant challenges in the future. Therefore, the Chinese economy needs to manage the population by putting the national family planning policy into practice and by paying special attention to the effect of population size on the environment.

The coefficient of residential energy consumption given the ICT level below the threshold value is 0.673, which is positive and significant at 10 percent, that is, a one percent increase in energy use in the residential sector causes carbon emissions to rise by 0.673 percent. On the other hand, the environmental effect of residential energy consumption moves towards deterioration given the level of ICT above the threshold level. With the increase in the use of ICT devices among households, the demand for electricity increases, which puts upward pressure on total energy demand. The invention of smartphones and portable devices including laptops and digital cameras with WiFi-enabled internet connectivity has provided accessibility to a larger range of activities [82,83]. Moreover, ICT uses energy, particularly when operating or installing equipment that requires electricity, thus it causes an increase in demand. ICT has facilitated many people to use social media applications such as YouTube and other websites as a source of earnings. TV and radio have been displaced by laptops and smartphones to watch movies and listen to music, which has led to an increase in ICT-related energy in the residential sector. Through the widespread adoption of E-life due to ICT advancements, activities previously carried out outside the home, for example, teleworking, online shopping, dining out, learning, and doctor consultations, are now conducted inside. This result is in line with the findings of Sadorsky (2012) [84] and Yu et al. (2020) [85], who observed that, in China, even after accounting for the energy savings from avoided travel, the rising popularity of online activities and services would result in a rise in household energy consumption of almost 18.1%.

Results show that, given the level of ICT below the threshold level, a 1 percent increase in the energy consumption in the transportation sector causes carbon emissions to increase by 1.273 percent; however, given the level of ICT above the threshold value, the effect of transportation energy consumption reduces to 0.785 percent. This is due to the fact that ICTs reduce the need for in-person interactions, which relieves pressure on energy usage and transportation-related activities. Our finding is in accordance with the study of Kouton (2019) [86] and Chatti and Majeed (2022) [87], who are of the view that the use of ICTs makes it easier to obtain travel information, use planning tools, share transportation, work from home, assess the expenses of transportation, and make payments online. In addition, since consumers may now shop online due to e-business, automobiles are used less frequently [88]. The use of ICT in the banking, education, health, and business sectors has made it easy for individuals to obtain information without commutation, thus reducing the use of energy in the transportation sector.

The findings of this study show that a 1 percent increase in energy consumption in the industrial sector, conditional on the low level of ICT, increases carbon emissions by 1.439 percent. The large value of the coefficient compared to the coefficient value of energy consumption in other sectors reveals that energy use by the industrial sector has a significant harmful effect on the environment. However, the value of the coefficient increases to 2.269 percent given the value of ICT above the threshold level. The results are in accordance with the findings of Nižetić et al. (2020) [89] and Taneja et al. (2021) [90]. With the increase in digitalization, industries are also going through digital transformation. The digital revolution in the industrial sector brings with it low-cost and energy-efficient production techniques. On the other hand, increased use of ICTs themselves may cancel out the impact of ICTs improving energy efficiency because a digitalized sector sees a rise in the use of digital components. Due to rebound effects, efficiency gains from technical advancement have failed to reduce the overall environmental burden of industrial production. Additionally, a growing amount of electricity is needed for the supporting infrastructure, such as data centers, networking hardware, cooling equipment, etc. Our result is in contrast with the findings of Liu et al. (2018) [91], who examined that, due to China's significant investment in improving carbon performance while altering the production technique of carbon-emitting industries, China has made an achievement in reducing carbon emissions.

5. Conclusions and Policy Implications

This study examines the effect of ICT on the environmental impact of energy consumption in different sectors of the Chinese economy. Based on the findings of this study, we infer that, in the case of the residential sector, an increase in the use of ICT above the threshold level results in environmental degradation due to energy intensity. The use of smartphones and laptops is increasing among households due to social media apps and entertainment websites. The use of ICT in the industrial sector also induces an energy rebound effect, due to which efficiency gains from technical advancement have failed to reduce the overall environmental burden of industrial production. In contrast, in the transportation sector, the use of ICT reduces energy intensity because the use of ICT by the banking, education, health, and business sectors has made it easy for individuals to obtain information without commutation, thus causing a decline in carbon emissions.

Due to the fast expansion of China's online economy, special attention must be paid to the potential impacts of ICT and the internet era on future energy requirements. Since a high level of ICT results in a rebound effect in residential and industrial energy consumption, based on the findings of the study, we recommend that the possibility of rebound effects should be given more attention in the development of policies regarding the digitalization of the residential and industrial sectors. The negligence of the ICT-induced rebound effect while making digital transformations increases the danger of endorsing ICTs as the solution to all environmental problems. Additionally, internet policy must be developed so that its effects on adoption, access, interactions, and reach are amplified in the transportation sector. The management of green and sustainable transportation can be aided by the integration of ICTs into the transportation sector in the form of transport-sharing applications, intelligent traffic controls, and eco-driving, thus lessening environmental impacts. ICT can be utilized to help the transition to a less transport-intensive lifestyle if it is accommodated by other policies aimed at reducing demand for transportation, including high taxes.

This study analyzes the environmental effects of ICT on energy consumption in different sectors of the economy using country-level data; however, future studies may conduct the same analysis using provincial data to observe the difference in the adoption and usage of ICT across the provinces.

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