Effects of ICT hardware, software and FDI on CO2 emissions in China

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Abstract

With the rapid development of information and communication technology (ICT) and counter-cyclical expanding of foreign direct investment (FDI), most foreign-invested companies in China are highly polluting. Meanwhile, new research shows that the impact of ICT on the environment is uncertain. This study is an effort in dividing ICT into hardware and software, aiming to explore its effects on CO_2 emissions from 2003 to 2017 in 31 provinces, autonomous regions and municipalities in China, and further explore the impacts of its application to foreign-invested enterprises on environmental quality. The findings show that ICT software specifies negative and statistically significant effects on CO_2 emissions, but ICT hardware and FDI indicate positive and statistically significant effects on CO_2 emissions. However, when ICT software and hardware are applied to foreign-invested enterprises, they can significantly improve the environmental quality. It is noteworthy that previous period of ICT software will increase current CO_2 emissions significantly, yet ICT hardware lagged three years will reduce current CO_2 emissions significantly.

Introduction

Excessive CO_2 emissions can lead to global warming, sea level rise, species reduction, frequent disasters, and break the balance of natural ecosystems. The severe situation of ecological environment is caused by the extensive mode of economic growth. Arrhenius (1896) indicated that the use of fossil fuels will inevitably increase the carbon emissions, and traditional industries around the world are based on fossil fuels.

According to the World Bank's estimate, China's carbon emissions made up about 30.9% of the world's total in 2020, ranking first. Some reports indicate that the earth's temperature is likely to rise 1.5 degrees centigrade by 2030, and more than 95% of the world's cities are highly vulnerable to climate change. These cities are centered largely in Asian and African countries. Given that China is the world's biggest carbon emitter, transforming China's economic growth mode can achieve a multiplier effect in solving the global environmental problems. In order to improve the environment and achieve green growth, China has to promote the transition of the economic growth mode from relying excessively on resource investment to relying on technology progress. Transformation of economic development model has a profound impact on China, especially the world. Information and Communication Technology (ICT) is the factor that not only reduces carbon emissions, but also helps nurture economic growth (Usama et al., 2015). With the fast pace of China's digitization, a new round of science and technology revolution led by ICT is in the ascendant, and the digital economy is thriving. In 2020, China's digital economy scale reached $5.4 trillion, accounting for 38.6% of GDP, ranking second in the world. The digital economy has broad application prospects in the field of green and low-carbon development. Intensive, efficient, smart and green ICT has become the pillar of economic transformation and innovative production (Khalifa, 2021), and has enormous potential for realizing economic sustainable development.

ICT mainly reduces CO_2 emissions by three aspects. First, ICT can be applied to manufacturers through power grid, smart motor system, transportation system, etc., which can improve production efficiency, optimize the production process, and achieve energy conservation and emission reduction. The second is the deep coupling of ICT software and network, which will change the service model and business model of enterprises, and reduce transaction costs, such as negotiation costs, product prices, transportation costs, etc. The third is the application of ICT to people' lives and studies, reducing the demand for traffic and office space, and having substituting function on the material(Hilty, 2008), such as video conference (Coroama et al., 2012), personal digital assistant (Toffel and Horvath, 2004), e-commerce, telework, etc. The "SMARTer2020" research report pointed out that by 2020 the extensive application of ICT can reduce global greenhouse gas emissions (GHG) by 16.5%. However, some researchers hold the opposite view. They believe that the popularization and application of ICT will greatly stimulate the demand for electricity, thereby increasing energy consumption, such as running servers and using data centers. Based on previous research, we find that the impact of ICT on the environment is still uncertain. Since exploring the impact of ICT on the environment can't draw valid conclusions, this study will divide ICT into hardware and software to further explore the impacts on carbon emissions, which will be a brand new breakthrough.

In 2020, China attracted FDI achieving counter-cyclical expanding, and surpassed the United States becoming the largest country absorbing the foreign capital. There are two hypotheses about the relationships between FDI and environmental pollution in the host country, namely the "Pollution Haven" hypothesis (Baumol and Oates, 1988) and the "Pollution Halo" hypothesis (Zarsky, 1999). The “Pollution Haven” hypothesis holds that the host country (usually developing countries) will formulate environmental policy to attract investment from strict environmental control countries (usually developed countries). Through the environmental pollution transfer mechanism, FDI increases the host country’s carbon dioxide emissions. The “Pollution Halo” hypothesis believes that FDI helps the host country’s enterprises to raise the production efficiency and the availability of resources through technology spillover over and substitution effect, thereby improving the host country’s environmental quality. Overall, the impact of China’s FDI on carbon dioxide emissions is in accord with the “Pollution Haven” hypothesis (Pei et al., 2021). Considering that foreign-invested enterprises in China mostly are highly polluting, it is of great practical significance to investigate the impact of foreign-invested enterprises using ICT hardware and software on CO_2 emissions.

The contribution of this research is to divide ICT into hardware and software to explore its impacts on CO_2 emissions, and introduce the interaction term to further explore the impacts of the application of ICT hardware and software to foreign-invested enterprises on environmental quality. This will be a totally new breakthrough. This research consists of five parts. In section 2, we cover the previous studies to highlight the theoretical significance of this study. In section 3, our focus is on data, models and methods. In section 4, we will discuss the outcomes of this study. In section 5, we summarize the research.

Literature Review

The relationships between economic factors and carbon dioxide emissions, as well as non-economic factors and carbon emissions, have been intensively analyzed empirically over the past two decades. From the economic factors’ point of view, factors that affect CO_2 emissions include economic growth, financial development, globalization, remittances, FDI etc. From the non-economic factors’ point of view, factors that affect CO_2 emissions include energy, tourism, system quality, ICT etc.

Economic factors and CO_2 emissions

Economic growth will increase carbon emissions (Basnet and Upadhyaya, 2014; Anzoategui et al., 2014; Chen and Taylor, 2020; Cazachevici et al., 2020), which is mainly due to four effects: scale effect, output effect, input effect and technique effect. On the basis of different research backgrounds, financial developments have different impacts on carbon emissions. Although Tamazian et al. (2009), Sadorsky (2011), Shahbaz et al. (2013a, 2013b) and Mallick and Mahalik (2014) indicated that with the development of finance it is more inclined to fund green technologies for energy conservation and emissions reduction, the literatures showed uncertainties about the influence of financial development on environment. On the one hand, as an important part of economic development, developed financial markets allow companies to take full advantage of financial resources to purchase manufacturing facilities and invest in new projects, increasing social energy use and expanding carbon emissions. On the other hand, the more developed the financial market, the higher the requirement for technical level, the lower the consumption of traditional energy and the improvement of environmental quality (Tamazian et al., 2009; Hsueh et al., 2013).

Globalization will destroy natural resources to achieve economic growth. Wijen and Tulder (2011), Doytch and Uctum (2016) and Saint Akadiri et al. (2019) investigated that globalization significantly and positively affect carbon emissions. Shahbaz et al. (2018) indicated that globalization will reduce carbon emissions for developed countries and increase carbon emissions for emerging countries. This may be related to the application of green technology.

At present, some researchers have extended the economic factors affecting CO_2 emissions to remittances. Basnet and Upadhyaya (2014), Ahmad et al. (2019) and Cazachevici et al. (2020) believe that as an important form of foreign capital inflow, remittances can raise the incomes of local people, promote economic and financial development, and thus increase CO_2 emissions. Researchers carry out research from the perspective of developed countries and emerging countries. The global value chain position reflects a country’s CO_2 emissions. Emerging economies are located in the low end of global value chain, and they participate in the global value chain by producing highly polluting and low value-added products. Advanced economies are located at the high end of global value chain, and they participate in the global value chain by producing less-polluting and high value-added products (Meng B et al., 2018; Sun C et al., 2019).

Shahbaz et al. (2018) showed that most countries try to accomplish their industrialization by attracting foreign direct investment and relying on foreign trade, consuming traditional energy resources to an extreme to promote rapid economic growth. This will inevitably affect the environmental quality of the whole country and lead to environmental degradation. There is a certain degree of causality between the country's industrialization and even urbanization and the decline in environmental quality. Yang et al. (2021) set out to study the relationship between FDI and home country's carbon dioxide emissions, and found that FDI is positively associated with home country's carbon dioxide emissions. The technological spillovers from FDI reduce CO_2 emissions to some extent. The empirical results of Adeel-Farooq et al. (2021) showed that FDI from developed countries will improve the environmental performance of low-to-middle income and upper-middle income countries, while FDI from developing countries is harmful to the environment of low- and middle- income countries. Abbas et al. (2021) regarded FDI as an integrated variable of regulatory quality (RgQ) and per capita energy consumption (EC). The findings showed that EC has negative impact on CO_2 emissions, while RgQ has positive impact on CO_2 emissions. Pei et al. (2021) applied dynamic spatial fixed-effects Durbin model to explore the correlation between FDI and PM 2.5. The results showed that PM 2.5 has significant spatial spillover effect, and "Pollution Haven" hypothesis is applicable to Chinese cities. The upgrading of industrial structure can adjust the relationship between FDI and PM 2.5 to a certain extent.

Non-economic factors and CO_2 emissions

The impact of energy use on the environment can basically reach a consensus. Pao and Tsai (2010), Saboori and Sulaiman (2013), Katircioğlu and Taşpinar (2017), Nasreen et al. (2017) and Haseeb et al. (2018) all believed that the use of energy can increase CO_2 emissions and worsen the environment. Most scholars believe that tourism can increase the CO_2 emissions (Katircioglu et al., 2014; Eyuboglu and Uzar, 2019). A lot of empirical researches have shown that transportation and accommodation can increase energy consumption and are important components of CO_2 emissions. Ecotourism is on the agenda (Shaheen et al., 2019). Nguyen and Su (2021) found that the improvement of system quality, especially the regulatory quality and government efficiency, will support environmental sustainability. At the same time, it was found that in countries with good system quality, the negative impact of international tourism on the environment will intensify.

Another important non-economic factor is information and communication technology (ICT). The impact of ICT on the environment is controversial. The deterioration of the environment caused by ICT is mainly reflected in three aspects. First, the application of ICT requires a lot of energy, such as mobile phones, data centers and smart grids (Houghton, 2010; Lennerfors et al., 2015). The second is the production of electronic waste (Houghton, 2010). Third, ICT can increase the productivity of economic factors, promote economic growth, consume a lot of energy, and thus worsen the environment (Danish et al., 2018). Some researchers believe that ICT may improve the environment, such as the introduction of energy saving and emission reduction technology, and green grids (Añón Higón et al., 2017). For example, 5G, artificial intelligence etc. have led to a substantial increase in communication data due to more Internet users, faster broadband speeds and higher video watching rates (Barnett, 2018).

Recently, N'dri et al (2021) regarded developing countries as the study object to explore the impact of ICT on the environment. Research showed that the use of ICT is beneficial to relatively low-income developing countries, but has no perceptible effect on relatively high-income developing countries. Zhang et al. (2021) used the CGE method to find that the application of ICT in Japan can achieve an extra 1% to GDP growth and a 4% reduction in greenhouse gas emissions by 2030, which means that ICT can decouple the economy from the environment. The conclusion is consistent with the estimated results of the Global e-Sustainability Initiative (GeSI, 2015). Usman et al. (2021) explored the impact of ICT on CO_2 emissions in 9 Asian countries from the perspective of symmetric or asymmetric effects. The findings showed that nearly half the countries recognize the symmetry of the short-term impact of ICT. In the long run, the asymmetric impact of more than half the countries needs further observation. The empirical results of Yan et al. (2021) showed that in a better market environment, the marginal effect of ICT investment on the upgrading of industrial structure is increasing. That is, with the high quality development of the market economy, ICT investment will play a more positive role in the upgrading of industrial structure. What is more, some scholars associate ICT with corruption. Fan et al. (2021) analyzed the data of more than 4000 enterprises in 76 countries and found that the development of ICT can significantly hinder illicit payments to regulators in corporate terms. Perez-Ramos et al. (2021) studies the use of ICT to tackle environmental health risks in marginalized communities. With the assistance of ICT, Greeen et al. (2021) designed and developed a mobile health education application for hypertensive patients to help the most vulnerable groups in India.

Based on review of the literature, it can be found that most recent studies on the impact of FDI on CO_2 emissions have focused on the introduction of new research objects or methods, such as the impact of FDI on carbon emissions of home country, and the impact of FDI from developed countries on carbon emissions in low- and middle- income countries. It is similar to the research on the impact of ICT on carbon emissions, such as the impact of ICT on carbon emissions in low and high income countries, using CGE method to study the relationship between ICT and carbon emissions etc. Few scholars have analyzed the impacts of ICT hardware and software on carbon emissions, and no one has gone deep into the impact of ICT hardware and software applied to foreign-invested enterprises on carbon emissions. The contribution of this study is to fill the blank by using system GMM estimation through adding of interaction term.

Data And Methodology

Data

In this research, panel data are used to analyze the effects of FDI, ICT hardware and software on CO_2 emissions from 2003 to 2017 in 31 provinces, autonomous regions and municipalities in China. Variables description and data sources are shown in Table 1.

The explained variable is CO_2 emissions of each province, which is calculated from the apparent consumption of fuel. The apparent consumption of fuel is related to the production, import, export and inventory change. Based on the relevant data of raw coal, crude oil and natural gas from China Energy Statistical Yearbook, the carbon emissions of each province can only be calculated until 2017.

The core explanatory variables are FDI, ICT hardware and software. ICT hardware includes computer and external device, communication equipment, integrated circuits, electronic components, etc. The deep integration of ICT hardware and real economy can cultivate highly automated business processes to reduce production costs, improve production efficiency, and have a positive impact on the environment. When investigating the effect of information and communication technologies (ICT) development on other factor, it is preferable to employ monetary measure (ICT investment) to represent ICT development (Ishida, 2015). Therefore, this indicator is measured by the ratio of fixed asset investment to gross production in the computer, communications and other electronic equipment manufacturing industries.

ICT software includes information transmission, software and information technology service. The deep integration of ICT hardware and real economy can transform big data into the power of insight and decision-making to promote new products and services, accelerate the development of new formats, such as networked collaborative R&D, large-scale customization, cloud manufacturing, etc. The ratio of fixed asset investment to gross production in the information transmission, software and information technology service industries is used as a substitution variable reflecting the development level of software.

Considering the requirements of regressions analysis on freedom degree, the control variables are set to two, namely energy consumption and the squared economic growth. Among them, energy consumption is the most important factor that reduces environmental quality (Cho et al., 2007; Apergis and Payne, 2010; Al-mulali et al., 2012; Lu, 2018; Rani and Kumar, 2018). The square of economic growth is based on the environmental Kuznet curve (EKC) hypothesis. Taking natural logarithms of all absolute values make the data more stable, eliminate the collinearity and heteroscedasticity of the model, and other values maintain its original form. The descriptive statistics for variables are displayed in Table 2.

Table 1

Variables description and data source .

	Symbol	Variable description	Units of measure	Data source
Explained variable	CO_2	Carbon dioxide emissions	Metric tons	Calculated from the apparent consumption of the fuel
Main explanatory variable	IH	ICT hardware	Fixed assets investment in computer, communication and other electronic equipment manufacturing(% of GDP)	Province Statistical Yearbook(2004–2018)
	IS	ICT software	Fixed assets investment in information transmission, software and information technology service industries(% of GDP)	Province Statistical Yearbook(2004–2018)
	FDI	Foreign direct investment	100 million US$	Province Statistical Yearbook(2004–2018)
Control variable	EG	Economic growth	Per capita GDP (Rmb 10000)	Province Statistical Yearbook(2004–2018)
	EC	Energy consumption	10000 tons of standard coal	China Energy Statistical Yearbook(2004–2018)

Table 2 Descriptive statistics for variables (2003-2017) .

	Variable	Mean	Std. Dev.	Min	Max
Explained variable	CO_2	1.397	0.499	0.649	2.026
Main explanatory variable	IS	0.009	0.006	0.000	0.051
	IH	0.006	0.008	0.000	0.050
	FDI	6.482	0.671	4.633	7.231
Control variable	EC	12.343	0.555	11.499	13.096
	EG^2	24.177	2.365	19.691	27.612
Note: There is data deficiency in ICT hardware and software, which is solved by the KNN interpolation.					

Methodology

To see the role of ICT hardware, software and FDI in affecting carbon dioxide emissions in China, we developed the benchmark regression model in specification (1).

$$CO_{2t} = \alpha_0 + \alpha_1 IS_t + \alpha_2 IH_t + \alpha_3 FDI_t + \alpha_4 EC_t + \alpha_5 EG_t^2 + \varepsilon_t$$

1

Among them, the explained variable is CO_2 emissions, and the core explanatory variables are ICT hardware, software and FDI represented by IH, IS and FDI. Energy consumption and the squared economic growth represented by EC and EG^2 are the control variables, which are considered to be key factors affecting CO_2 emissions.

To examine the impact of foreign-invested enterprises using ICT hardware and software on carbon dioxide emissions, we specify the interactive model (2) based on previous studies by Wang et al. (2019), which used this model to examine interactive variable relationship.

$$CO_{2t} = \beta_0 + \beta_1 IH_t + \beta_2 FDI_t{*}IS_t + \beta_3 EC_t + \beta_4 EG_t^2 + \varepsilon_t$$

2

FDI*IS represents the interaction term of foreign direct investment and ICT software, hence β_2 means the extent that ICT software increases or decreases the impact of foreign direct investment on CO_2 emissions. In particular, we can use the coefficient estimates to judge the influence direction of foreign-invested enterprises using ICT software and hardware on CO_2 emissions. If $\beta_2 > 0$, foreign-invested enterprise using ICT software will increase carbon emissions. If $\beta_2 < 0$, foreign-invested enterprises using ICT software will reduce carbon emissions. The same is true for ICT hardware.

Empirical results

For short panel data, that is, large N and small T, Blundell and Bond (1998) developed a system GMM estimation. This method can solve the potential endogenous problem in the model and make full use of sample information, which makes the estimation results have better finite sample properties.

From model (1) of Table 3, we can get the estimated results of system GMM. ICT software specifies negative and statistically significant effects on CO_2 emissions for China. ICT hardware indicates a positive and statistically significant effect on CO_2 emissions. It shows that the popularization and upgrading of ICT hardware is hurting the environmental quality, such as computers, mobile phones, televisions, audio-visual aids, etc. However, the increasing of ICT software scale helps in reducing CO_2 discharges. The finding implies that ICT software has the ability to change the economy from tangible products to intangible products, which in turn reduces the economy's demand for tangible products, reducing CO_2 emissions (Yu et al., 2018). FDI has a positive and statistically significant effect on CO_2 emissions in the long run, which are in line with the findings of the studies by Jun et al.(2018) in China, Kamran et al.(2019) in Pakistan, Terzi and Pata(2020) in Turkey, Ali et al.(2021) in Pakistan etc. For the control variables, energy consumption has a positive impact on CO_2 emissions, which is consistent with expectations. Quadratic economic growth has a significant negative impact on CO_2 emissions, which verifies the validity of EKC hypothesis. That is, an inverse U-shaped relationship exists between economic growth and CO_2 emissions. This further certifies the results of the studies by Seker et al. (2015) in Turkey, Liu (2020) in China, Ali et al. (2020) in Pakistan etc.

From estimated results of model (I) and (II) in Table 3, some original discoveries are made in the course of research. First, previous period of ICT software will increase current CO_2 emissions significantly. Second, ICT hardware lagged three years will reduce current CO_2 emissions significantly. This shows that from the perspective of energy efficiency durative innovation of ICT software ensures environmental sustainability while reducing the energy consumption. That is, time-sensitive software will reduce carbon emissions (Ahmed, 2020). At the same time, software services possess scale economy, which can promote application subject's scale economy (Ferreira et al., 2009). However information software backward development will cause serious waste of resources, increasing carbon emissions. For ICT hardware, most hardware devices have adopted energy-saving techniques (Tuysuz and Trestian, 2020). From this, the use of old energy-saving equipment will be more environmentally friendly, compared to the production of new energy-saving equipment.

Table 3 System GMM estimates of the benchmark regression model.

Explanatory Variables	Model (1)	Model (I)	Model (II)
IS	-0.075***	0.039***	
	(-6.51)	(3.67)	
IS(-1)			0.039***
			(4.22)
IH	0.015***		0.011***
	(7.09)		(4.98)
IH(-3)		-0.010***	
		(-3.46)	
FDI	0.081***	0.024***	0.051***
	(18.27)	(4.71)	(10.63)
EC	0.625***	0.649***	0.650***
	(173.50)	(181.99)	(187.04)
EG^2	-0.005***	-0.004***	-0.004***
	(-19.63)	(-18.42)	(-17.39)
AR(1)	0.024	0.000	0.000
	($P < 0.1$)	($P < 0.1$)	($P < 0.1$)
AR(2)	0.683	0.441	0.390
	($P > 0.1$)	($P > 0.1$)	($P > 0.1$)
Sargan	0.000	0.000	0.000
	($P < 0.1$)	($P < 0.1$)	($P < 0.1$)

Notes: *, **, *** indicate that the influence coefficients pass the significance test at the level of 10%, 5%, and 1% respectively.

In this study, we also want to examine the impact of ICT software and hardware applied to foreign-invested enterprises on CO_2 emissions. Therefore after completing our debate on estimation results of the benchmark regression model (1), we will start in on discussing the estimation results of the interactive model (2) in Table 4.

From estimation results of interactive regression model in Table 4, we find that FDI*IS indicates a negative and statistically significant effect on CO_2 emissions. That is, when ICT software is applied to foreign-invested enterprises, the influence coefficient of FDI on CO_2 emissions is -0.016, and is significant. FDI*IH has a negative and statistically significant effect on CO_2 emissions in model (□). That is, when ICT hardware is applied to foreign-invested enterprises, the influence coefficient of FDI on CO_2 emissions is -0.019, and is significant. It shows that when ICT software and hardware are applied, foreign-invested enterprises will reduce carbon emissions, and the effect of using ICT software is roughly the same as that of ICT hardware. Compared to hardware, the application of software technology can promote transformation and upgrading of manufacturing-based foreign-invested enterprises. The importance of software is increasing across a wide array of manufacturing industries, and software has become an increasingly important input factor for innovation. The more software-intensive manufacturing enterprises, the more patents they generate, the more carbon emissions are reduced (Branstetter et al., 2019). For example, in the automotive field, ICT software administers everything, from fuel, carbon emissions to the power antenna of the car. ICT hardware directly improves production efficiency and reduces artificial cost. For the control variables, energy consumption has a significant positive impact on CO_2 emissions, and the square of economic growth has a significant negative impact on CO_2 emissions. This is basically accordant with the benchmark regression model’s estimated results.

Table 4 System GMM estimates of the interactive regression model.

Explanatory Variables	Model (2)	Model (3)
IS	-0.085*** (-6.81)	0.005 (0.41)
IH	0.106*** (15.72)	0.014*** (6.53)
FDI*IH	-0.019*** (-15.52)	
FDI*IS		-0.016*** (-18.16)
EC	0.645*** (189.99)	0.629*** (180.50)
EG^2	-0.005*** (-17.82)	-0.004*** (-19.45)
AR(1)	0.000 ($P < 0.1$)	0.031 ($P < 0.1$)
AR(2)	0.951 ($P > 0.1$)	0.639 ($P > 0.1$)
Sargan	0.000 ($P < 0.1$)	0.000 ($P < 0.1$)

Notes: *, **, *** indicate that the influence coefficients pass the significance test at the level of 10%, 5%, and 1% respectively.

The following robustness tests are carried out to ensure the robustness of the estimation results. First, the data in 2008 is eliminated to mitigate the effect of American Financial Crisis on the estimation results during the sample period, as shown in Table 5. Secondly, in addition to choosing the investment of foreign-invested enterprises as a measure of FDI, the registered capital of foreign-invested enterprises is also used as an alternative variable of FDI, as shown in Table 5. Finally, in order to deal with the possible extreme values, ICT software, hardware and FDI are subjected to bilateral tail reduction at 1%level. Based on the analysis above, it can be concluded that the coefficient signs and significance of the core explanatory variables have not changed essentially, such as ICT software, hardware and ICT. Thus it is confirmed that empirical results of the benchmark regression model are robust.

Table 5 Robustness test.

Explanatory Variables	Eliminate special values			Substitute core explanatory variable			Bilateral tail reduction at 1% level		
	(1)	(I)	([illegible])	(1)	(I)	([illegible])	(1)	(I)	([illegible])
IS	-0.049***	-0.071***		-0.067***	-0.068***		-0.072***	-0.069***	
	(-5.27)	(-7.79)		(-5.68)	(-6.58)		(-6.21)	(-5.88)	
IH	0.045***		0.008***	0.023***		0.007***	0.032***		0.009***
	(4.28)		(3.32)	(5.21)		(3.57)	(4.67)		(3.21)
IS(-1)			0.032***			0.028***			0.029***
			(3.30)			(2.98)			(3.00)
IH(-3)		-0.009***			-0.012***			-0.010***	
		(-2.48)			(-3.21)			(-2.98)	
FDI	0.076***	0.021***	0.047***	0.081***	0.018***	0.053***	0.072***	0.023***	0.049***
	(12.05)	(3.54)	(8.94)	(18.27)	(4.21)	(9.21)	(15.03)	(3.98)	(7.98)
EC	0.642***	0.639***	0.652***	0.625***	0.592***	0.621***	0.621***	0.600***	0.615***
	(157.76)	(171.80)	(180.21)	(173.50)	(170.20)	(160.54)	(168.21)	(169.21)	(178.21)
EG^2	-0.004***	-0.004***	-0.003***	-0.005***	-0.005***	-0.004***	-0.005***	-0.004***	-0.003***
	(-12.06)	(-14.06)	(-13.12)	(-19.63)	(-15.05)	(-14.21)	(-16.21)	(-15.21)	(-12.15)
AR(1)	0.031	0.001	0.003	0.012	0.003	0.001	0.015	0.005	0.002
	($P < 0.1$)	($P < 0.1$)	($P < 0.1$)	($P < 0.1$)	($P < 0.1$)	($P < 0.1$)	($P < 0.1$)	($P < 0.1$)	($P < 0.1$)
AR(2)	0.102	0.201	0.300	0.261	0.171	0.243	0.683	0.683	0.683
	($P > 0.1$)	($P > 0.1$)	($P > 0.1$)	($P > 0.1$)	($P > 0.1$)	($P > 0.1$)	($P > 0.1$)	($P > 0.1$)	($P > 0.1$)
Sargan	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
	($P < 0.1$)	($P < 0.1$)	($P < 0.1$)	($P < 0.1$)	($P < 0.1$)	($P < 0.1$)	($P < 0.1$)	($P < 0.1$)	($P < 0.1$)

Notes: *, **, *** indicate that the influence coefficients pass the significance test at the level of 10%, 5%, and 1% respectively.

Different economic development status quo and marketization degree may affect the influence of ICT software, hardware and FDI on CO_2 emissions. Therefore, this paper explores the difference between the impact of ICT software, hardware and FDI on CO_2 emissions in the eastern, central and western regions. As can be seen from Table 6, the estimated coefficients of ICT software and hardware on CO_2 emissions are all significantly negative in the eastern provinces, indicating that the improvement effect of ICT software and hardware on environment in the eastern region is stronger than that in the central and western regions. The reason is that compared with the central and western region, the economy in the east is better-developed and production technique is more advanced. Enterprises in the eastern region have the stronger environmental protection consciousness, and their most hardware devices have adopted energy-saving techniques (Tuysuz and Trestian, 2020). The government and non-governmental environmental protection organizations can better supervise and restrict carbon footprint from businesses. Therefore, the estimated coefficients of ICT software and hardware on CO_2 emissions are all significantly negative in the eastern provinces.

Table 6 Empirical results of different regions.

Explanatory Variables	Eastern	Central	Western
IS	-0.045**	0.039**	0.042***
	(-2.04)	(2.00)	(3.18)
IH	-0.013**	-0.027***	0.002
	(-2.28)	(-4.25)	(0.78)
FDI	0.030***	-0.063***	0.049***
	(2.57)	(-3.18)	(6.30)
EC	1.029***	1.216***	0.576***
	(72.76)	(46.20)	(145.99)
EG^2	-0.004***	-0.001	0.022***
	(-15.22)	(-0.49)	(19.38)
AR(1)	0.000	0.059	0.000
	(P < 0.1)	(P < 0.1)	(P < 0.1)
AR(2)	0.476	0.531	0.620
	(P > 0.1)	(P > 0.1)	(P > 0.1)
Sargan	0.000	0.000	0.000
	(P < 0.1)	(P < 0.1)	(P < 0.1)

Notes: *, **, *** indicate that the influence coefficients pass the significance test at the level of 10%, 5%, and 1% respectively.

Conclusions

This study explores the effects of ICT software and hardware and its application to foreign-invested enterprises on CO_2 emissions from 2003 to 2017 in 31 provinces, autonomous regions and municipalities in China. Estimated results of system GMM indicate that ICT software specifies negative and statistically significant effects on CO_2 emissions. ICT hardware indicates a positive and statistically significant effect on CO_2 emissions. FDI has a positive and statistically significant effect on CO_2 emissions. We have some new findings in the course of research. First, the previous period of ICT software will increase the current CO_2 emissions significantly. Second, ICT hardware lagged three years will reduce the current CO_2 emissions significantly. When robustness examination is conducted, the coefficient signs and significance of core explanatory variables on CO_2 emissions have not changed essentially.

The estimated results of interactive regression model indicate that FDI*IS indicates a negative and statistically significant effect on CO_2 emissions. That is, when ICT software is applied to foreign-invested enterprises, the influence coefficient of FDI on CO_2 emissions is -0.016, and is significant. FDI*IH has a negative and statistically significant effect on CO_2 emissions. That is, when ICT hardware is applied to foreign-invested enterprises, the influence coefficient of FDI on CO_2 emissions is -0.019, and is significant. It shows that when ICT software and hardware are used, foreign-invested enterprises will reduce CO_2 emissions, and the environment improvement brought by the use of ICT software is roughly the same as that of ICT hardware. For the control variables, the estimated results of energy consumption and the square of economic growth on CO_2 emissions are in line with expectations. That is, energy consumption has a significant positive impact on CO_2 emissions, and the square of economic growth has a significant negative impact on CO_2 emissions, which verifies the existence of EKC hypothesis.

There are discrepancies in regard to the effect of ICT software and hardware on CO_2 emissions in different regions. The estimated coefficients of ICT software and hardware on CO_2 emissions are all significantly negative in the eastern provinces, indicating that the improvement effect of ICT software and hardware on environment in the eastern region is stronger than that in the central and western regions.

According to these empirical results, we propose some corresponding policy implications. ICT software reduces CO_2 emissions while ICT hardware increases CO_2 emissions in China. Policymakers should separate the effects of ICT software and hardware while formulating ICT policies. And ICT software should give a full play in improving the environment. Encourage the durative innovation of ICT software, which helps to improve the quality of the environment. For ICT hardware, the replacement rate should be appropriately reduced, due to waste electrical and electronic equipment (WEEE) and huge amounts of carbon dioxide emitted by making new electronic equipment (Hertwich and Roux, 2011; Park et al.,2019). For a number of foreign enterprises entering China, policymakers should support the use of efficient and environment-friendly technologies, such as ICT software and hardware, besides making tight environmental regulations to restrict the entry of high-pollution industries. At the same time, attention is paid to the application of ICT software, which can further improve environmental quality. Moreover, China should speed up the adoption of ICT, especially for the foreign-invested enterprises, which can upgrade the industrial structure and improve conditions.

For future studies, more empirical analysis can adopt the system GMM, which would provide application test concerning the relationship between ICT and environment quality. In addition, the study only regards China as the study object. Future studies can be extended to more developing countries to get a more universal conclusion. These countries can bring in foreign capitals while improving environmental quality. At the same time, the integration of ICT and the real economy still needs to overcome many challenges, which will be a long term process.

Declarations

Ethical Approval and Consent to Participate Not applicable

Consent to Publish Not applicable

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