Geoscience Frontiers 15 (2024) 101644

Contents lists available at ScienceDirect

Geoscience Frontiers

journal homepage: www.elsevier.com/locate/gsf

Research Paper

Digital economy and carbon dioxide emissions: Examining the role of threshold variables

Qiang Wang [a,*], Jiayi Sun [a], Ugur Korkut Pata [b], Rongrong Li [a], Mustafa Tevfik Kartal [c,d,e]

[a] School of Economics and Management, China University of Petroleum (East China), Qingdao 266580, China
[b] Osmaniye Korkut Ata University Faculty of Economics and Administrative Sciences, Department of Economics, Merkez, 80000 Osmaniye, Turkey
[c] Department of Banking and Finance, European University of Lefke, Lefke, Northern Cyprus, TR-10 Mersin, Türkiye
[d] Adnan Kassar School of Business, Lebanese American University, Beirut, Lebanon
[e] Department of Economics and Management, Khazar University, Baku, Azerbaijan

ARTICLE INFO

Article history:
Received 23 December 2022
Revised 14 February 2023
Accepted 31 May 2023
Available online 5 June 2023

Keywords:
Digital economy
Natural resource rent
Anticorruption regulation
CO_2 emissions
Threshold regression

ABSTRACT

Considering that previous literature has mainly focused on the impact of the digital economy (DE) on environmental degradation, ignoring the role of natural resources, this study uses two key factors (natural resource rent and anticorruption regulation) as threshold variables to reveal the effect of natural resources on the association between DE and carbon dioxide (CO_2) emissions. In doing so, the study covers 97 countries, uses annual data between 2003 and 2019, and applies a panel threshold model. The outcomes present that the influence of the DE on CO_2 emissions has a single-threshold effect (i.e., there is an inverted U-shaped link between the DE and CO_2 emissions) when natural resource rent is the threshold variable. Specifically, the DE significantly increases CO_2 emissions when the natural resource rent is at a low-to-medium level, but the DE suppresses CO_2 emissions growth when natural resource rent exceeds the threshold. Moreover, the DE drives overall CO_2 emissions growth when anticorruption regulation is the threshold variable and there are double thresholds for its impact on CO_2 emissions. Specifically, a rise in anticorruption regulation initially exacerbates the contribution of DE impact on CO_2 emissions and then weakens it over time. Based on the results, the study proposes various implications, such as formulating a DE development strategy, considering natural resources in the development of the DE, and strengthening anti-corruption efforts in the field of environmental protection.

1. Introduction

With the acceleration of excessive consumption and production activities, the massive CO_2 emissions have brought negative influences on human production and life, as well as economic and social life (Wang et al., 2023a, b, c). According to British Petroleum (2022), CO_2 emissions from energy use, industrial processes, combustion, and methane rose by 5.7% to 39 billion tons of CO_2 equivalent in 2021. Given the increasingly serious global climate issues, promoting low-carbon development has become a general consensus (Wang et al., 2023a, b, c). The definition of the DE can be stated as "*a broad range of economic activities that use digitized information and knowledge as key factors of production, modern information networks as an important activity space, and information and communications technology to drive productivity growth*" (Li et al., 2020). With further progress in information and communication technologies (ICT), the DE, with its high degree of innovation, strong penetration, and wide dissemination, has significantly altered the global economic structure, global competitive environment, and the global reorganization of factor resources, but its environmental impact is uncertain. The DE can have the capability in promoting low-carbon development from various aspects, such as government governance and enterprise transformation.

The DE has greatly improved the government's ability to monitor CO_2 emissions and low-carbon governance by integrating data resources, enhancing technical resources, and helping to build data network systems. Second, the DE can lead the green process and service innovation, improve production efficiency and carbon efficiency of enterprises, and provide the impetus for low-carbon economic transformation. On the other hand, with the increase of online activities, such as cloud computing and cashless payment systems, the demand for digital services is also growing. According to studies, the share of pollutant emissions from the global ICT industry will grow from 1%–1.6% in 2007 to more than 14% in 2040, with digital technologies essentially leading to more CO_2 emissions. For example, Salahuddin and Alam (2015) determined

* Corresponding author at: School of Economics and Management, China University of Petroleum (East China), Qingdao 266580, China.
E-mail address: wangqiang7@upc.edu.cn (Q. Wang).

https://doi.org/10.1016/j.gsf.2023.101644
1674-9871/

that ICT is the foundation of the DE, and its development leads to elevated electricity consumption, which increases local CO_2 emissions.

As a key physical foundation of the economy and society, strengthening innovation in natural resource management in the context of climate change is crucial to achieving high-quality social and economic advancement, sustainable transformation, and CO_2 emissions reduction. Because resources are a public good, the property rights to them are owned by the state, and most states have a monopoly on managing resource revenues. For this reason, the government often interferes too much in the production of the resource sector, while firms voluntarily or forcibly participate in corruption to secure their profits (Kolstad and Søreide, 2009). Some studies have shown that poor institutional quality increases transaction costs and reduces the efficiency of property rights (Deacon and Mueller, 2006). At the same time, natural resources usually generate resource rents due to their factor specificities, such as scarcity rents due to price increases from rapid demand growth, and depletion rents due to price increases from decreasing supply. Monopoly rents also arise from monopolies caused by large-scale development methods that are more profitable than other industries and whose benefits are in the hands of a few, and from resource-abundant regions. The high expected returns and low opportunity costs of rent-seeking and competition among various stakeholders for control of resources and their revenues reduce productive incentives (van der Gaag and Snijders, 2003), and when potential rent-seekers in society compete for economic rents, rent-seeking leads to corruption.

Even though studies have started to empirically examine the environmental influence of DE, some questions still exist as follows. (i) what type of impact does DE development have on CO_2 emissions in various countries; (ii) does DE have either a linear or non-linear impact on CO_2 emissions; (iii) since the price of natural resources remains on a long-term upward trend, economic rental returns from resource-rich and resource-poor countries can vary widely; (iv) does a change in natural resource rents have a threshold effect on the impact of the DE upon CO_2 emissions? Meanwhile, numerous studies in the literature show that a certain degree of corruption is inevitable as economic growth goes on (Sinha et al., 2019; Ganda, 2020; Xie et al., 2023), which exacerbates pollution through distorted resource allocation and loosening enforcement of environmental regulations. So, does anti-corruption regulation also lead to a threshold influence on the impact of DE over CO_2 emissions? These are questions worth exploring in depth.

This study explores the association of DE with CO_2 emissions by following up a comprehensive approach. In this way, this study provides the following contributions: (i) The study considers the effect of natural resources in the investigation of the association between DE and CO_2 emissions. In this context, the study uses natural resource rent and anticorruption regulation as threshold variables. (ii) The study applies a panel threshold regression for the empirical examination. (iii) The study includes 97 countries and uses yearly data from 2003 to 2019. Hence, the study presents empirical findings for a wide range of countries.

The study has the following sections: a literature review in the second section, a model construction in the third section portraying also data sources, an empirical test in the fourth section, a robustness test in the fifth section, and a conclusion and pertinent recommendations in the sixth section.

2. Literature review

2.1. An overview of the digital economy

A so-called DE is an economic form characterized by emerging digital technologies, which shows that emerging technologies are the core feature of digital economies. The definition of the DE has evolved with technological development and social progress. In the early phases, it was mainly the "Internet economy" based on the Internet. By comparing the differences between the new and old economies, Carlsson (2004) states that the new economy, digitalization, and the Internet are general-purpose technologies that enable a multitude of new combinations. Moriset and Malecki (2009) argue that the DE connects all aspects of business through the Internet and reduces dependence on geographic location. The second phase is primarily an ICT-oriented "information economy," in which the manufacturing and service industries that receive, transmit, and display data and information electronically are referred to as ICT industries. It includes basic innovation sectors such as semiconductors and processors, key technology manufacturing sectors such as computers and telecommunications equipment, and infrastructure production sectors (e.g., Internet and telecommunications networks) (OECD, 2015). ICT is an important factor in the rapid growth of global e-commerce transactions, and the rise of ICT and information technology infrastructures is affecting the purchasing habits of Internet users. The third phase is mainly a "DE" focusing on digital technologies, which, according to Chen (2020), are changing the way markets operate and lowering costs, while also creating new challenges for competition and intellectual property protection in the DE. Based on this, the authors propose policy recommendations to enhance the market performance of the DE, drawing on the latest insights from industrial economics. Jiang (2020) analyzes the role of digitalization in combating the new epidemic of coronary pneumonia in China, pointing out that digital technology can improve the ability to respond to the epidemic in the short term. Digital technology will become a key factor in the development of the industrial Internet of Things (IoT) and the integration of the consumer Internet, manufacturing, and service industries in the long term. Also, digital technology can provide the technological infrastructure for the convergence of the Internet, manufacturing, and services, which will have a positive influence on the flourishing of digitalization in China.

The two fundamental characteristics of the DE are digital platforms and digital data. Digital data is the new energy of digitalization, resulting from the digital footprints of personal, social, and business activities on various data platforms. Digital platforms are the foundation of the DE, providing mechanisms to bring a group of participants together for online interactions, and platform-centric enterprises have important advantages in a digitally driven economy. They can capture and extract data about platform users' online behavior and interactions, collect and analyze digital data, and then monetize that data to generate revenue.

2.2. DE-CO_2 emissions relationship

Research on CO_2 emissions first began in 1981 (Abeydeera et al., 2019), and publications in the field have shown a rapid growth trend after some scientists found that the main cause of climate change is CO_2 emissions. Most studies about CO_2 emissions have examined the role of various factors, such as economic growth, urbanization, and natural resource rent. The representative hypothesis on the impact of economic growth on the environment is the Environmental Kuznets Curve (EKC), proposed by Grossman and Krueger (1991), which states that economic development leads to pollution when economic development is low and suppresses pollution through the green effect when economic development exceeds a certain threshold. On this basis, many scholars have conducted empirical studies based on EKC for CO_2 emissions. For example, Pata (2018) used Turkish data from 1996 to 2011 as a research sample and found an inverted U-shaped effect of economic growth on CO_2 emissions.

Regarding the impact of energy consumption on CO_2 emissions, Acheampong (2018) applied a panel data analysis technique for 116 countries from 1990 to 2014 for various regions and found that energy consumption stimulates CO_2 emissions in the MENA region and significantly reduces pollution in the Africa and Caribbean-Latin America regions. Wu et al. (2016) concluded that the urbanization rate increases CO_2 emissions. As for natural resource rent, most studies conclude that natural resources increase CO_2 emissions to some extent. For example, Huang et al. (2021) found that natural resource rent increases CO_2 emissions. In contrast, some studies, such as Adebayo et al. (2023) argued that natural resources can contribute to CO_2 reduction.

Little attention has been paid in the literature to the impact of DE, a new form of economic development, on CO_2 emissions (Wang et al., 2022a). Although several studies have examined the impact of DE on CO_2 emissions, they have not provided an in-depth analysis (Zhang et al., 2022a). Empirical researches about the impact of DE on CO_2 emissions are controversial. On the one hand, DE can promote energy efficiency and carbon minimization by promoting technological progress and efficiency; on the other hand, the development of DE can lead to an increase in CO_2 emissions by expanding the scale of production (Li and Wang, 2022). Digital technologies can facilitate the management of CO_2 emissions by encouraging the use of public transport, better planning traffic routes, and changing the use of clean energy (Lee et al., 2022). DE development promotes the regulation of carbon emissions and energy costs through carbon trading rights and taxation (Wang et al., 2022a). As an important indicator of digitization, ICT diffusion can support progress in energy infrastructure, facilitate the adoption of renewable energy technologies and resources, and improve environmental quality (Murshed, 2020). By replacing digital media with traditional media, ICT can optimize energy use and thus contribute to minimizing environmental degradation (Dogan and Pata, 2022). With the advent of ICT, such as artificial intelligence, big data, blockchain, and cloud computing, countries and societies have been gradually moving from the traditional economy to the DE. But while the DE is booming, its environmental impact is multifaceted. This part of the literature is presented in Table 1, which shows that the existing research can be divided into three categories. First, the development of DE reduces CO_2 emissions (Li et al., 2021a; Chen, 2022a; Zhang et al., 2022b). Second, the impact of the DE on CO_2 emissions may be nonlinear, as some scholars have found an inverted U-shaped relationship between the DE and pollution through model-theoretic derivation (Piao and Cui, 2020; Li et al., 2021b; Kong et al., 2022; Xiang et al., 2022). Third, ICT raises CO_2 emissions (Salahuddin and Alam, 2015; Usman et al., 2021). According to these researchers, the DE first stimulates and then reduces CO_2 emissions, and there is regional heterogeneity (Li and Wang, 2022).

The reason for the differences in the research results could be the different ways of measuring the indicators. Here, the indicators refer to the DE, and the existing studies mainly use single indicators or comprehensive indicators to evaluate the comprehensive index of the DE. Single indicators are mainly measured by Internet usage rate, ICT import and export volume, and cell phone penetration rate. The comprehensive indicators method is based on digital infrastructure, digital industrialization, digital institutional environment, industry digitalization, digital business ecology, and other dimensions to build a system of indicators, and uses the entropy method or principal component analysis and other methods to calculate the comprehensive DE index, which may give different results from different angles.

2.3. Natural resource rent-CO_2 relationship

Existing literature measures natural resource rent as the difference between the benefits of natural resources and the costs of extraction. Natural resource rent is often discussed from the viewpoint of its economic, social, and environmental impacts. Some of this literature focuses on the impact of natural resource rent on CO_2 emissions, but these studies do not reach a consistent conclusion (see Table 2 for an overview of the literature).

Some of the literature argues that natural resource rent promotes CO_2 emissions (Bekun et al., 2019; Wang et al., 2020; Agboola et al., 2021; Shen et al., 2021; Zhang et al., 2022c), while others conclude that resources have a carbon-reducing effect (Joshua and Bekun, 2020; Tufail et al., 2021; Zhang et al., 2021; Safdar et al., 2022; Sicen et al., 2022). There are studies with conflicting views for the same group of countries. For example, Adebayo et al. (2023) emphasize that natural resources bring environmental benefits to BRICS countries, while Caglar et al. (2022) find that natural resource rent increases CO_2 emissions for that group of countries. Ulucak et al. (2020), Adebayo et al. (2022), and Li et al. (2022) also argue that natural resources have an increasing effect on CO_2 emissions.

There are also studies in the literature that find heterogeneity in the link between natural resource rent and CO_2 emissions. Danish et al. (2019) find heterogeneity in the impact of natural resource rent on CO_2 emissions in BRICS countries. The natural resource rent reduces CO_2 emissions in Russia but increases pollution in South Africa. Nwani and Adams (2021) introduce the variable of the degree of governance and find that in countries with poor governance, natural resource rent significantly increases CO_2 emissions

Table 1
Related literature on digital economy and environment.

Study	Method	Scope	Finding
Salahuddin and Alam (2015)	ARDL bounds test	Australia	ICT ↑ CO_2
Piao and Cui (2020)	STIRPAT model	China	Inverted U-shaped link between DE & CO_2
Li et al. (2021a)	STIRPAT model	30 provinces in China	Inverted U-shaped link between DE & CO_2
Li et al. (2021b)	Fixed-effect model	190 countries	Inverted U-shaped link between DE & CO_2
Chen (2022a)	ARDL approach	BRICS economies	DE ↓ CO_2
Chen (2022b)	Double fixed-effect model	Chinese manufacturing companies	DE ↓ CEI
Dogan and Pata (2022)	Cross-sectional ARDL	G7 countries	ICT ↑ EQ
Kong et al. (2022)	OLS robust standard error regression	15 RCEP countries	Inverted U-shaped link between DE & CO_2
Li and Wang (2022)	SDM and panel threshold model	274 prefecture-level cities in China	Inverted U-shaped link between DE & CO_2
Ma et al. (2022)	Nonparametric quantile regressions	30 Chinese provinces	DE ↓ CO_2
Usman et al. (2021)	Non-linear ARDL	9 Asian economies	ICT ↑ CO_2
Xiang et al. (2022)	Two-way fixed effect model	30 provinces in China	Inverted U-shaped link between DE & low-carbon, inclusive growth
Zhang et al. (2022a)	Fixed-effect model	Resource-based cities	DE ↓ CO_2
Zhang et al. (2022b)	Threshold model, and spatial Durbin model	277 cities in China	DE ↓ CO_2

Note: CEI: Carbon emission intensity. DE: Digital economy. EQ: Environmental quality. ↓: decreasing impact. ↑: increasing impact.

Table 2
Related literature on natural resource rent and environment.

Study	Methods	Scope	Finding
Bekun et al. (2019)	PMG-ARDL	EU-16 countries	NRR ↑ CO_2
Joshua and Bekun (2020)	ARDL bounds test	South Africa	NRR ↑ CO_2
Ulucak et al. (2020)	AMG estimator	26 OECD countries	NRR ↑ CO_2
Wang et al. (2020)	CS-ARDL	G7 countries	NRR ↑ CO_2
Agboola et al. (2021)	ARDL bounds test	Saudi Arabia	NRR ↑ CO_2
Nwani and Adams (2021)	AMG estimator	93 countries	NRR ↑ CO_2
Shen et al. (2021)	CS-ARDL	30 provinces in China	NRR ↑ CO_2
Tufail et al. (2021)	Westerlund cointegration	7 OECD countries	NRR ↓ CO_2
Zhang et al. (2021)	DARDL	Pakistan	NRR ↓ CO_2
Caglar et al. (2022)	CUP-FM & CUP-BC	BRICS economics	NRR ↑ CO_2
Safdar et al. (2022)	FMOLS and DOLS	6 South Asian countries	NRR ↑ GHG
Adebayo et al. (2022)	Fourier quantile causality test	Thailand	NRR ↑ CO_2
Li et al. (2022)	CS-ARDL	15 South East Asian countries	NRR ↑ CO_2
Sicen et al. (2022)	FM-OLS	BRICS economies	NRR ↓ CO_2
Zhang et al. (2022c)	CS-ARDL	48 developing countries	NRR ↑ CO_2
Adebayo et al. (2023)	CS-ARDL	BRICS economics	NRR ↓ CO_2

Note: GHG: Greenhouse gas emissions. NRR: Natural resources rent. ↓: decreasing impact. ↑: increasing impact.

based on production and consumption. Their results also show that natural resource rent has no significant effect on CO_2 emissions based on consumption in countries with good governance.

2.4. Corruption-CO_2 emissions relationship

Numerous studies have looked at the connection between corruption and CO_2 emissions over the past 20 years. It is generally agreed that corruption can contribute both directly and indirectly to environmental deterioration (Ganda, 2020). Using panel data from 94 countries, Cole (2007) found that corruption increases CO_2 emissions directly and reduces them indirectly by hindering economic growth. Using panel data from 22 European countries from 1999 to 2001, Pellegrini and Gerlagh (2006) revealed that corruption significantly worsens pollution by weakening the direct effect of environmental regulation, while the indirect effect of corruption on the environment comes from changing the structure of government spending. A study by Sekrafi and Sghaier (2018) found that controlling corruption contributes to economic growth and that this effect can indirectly reduce CO_2 emissions, but the direct effect of controlling corruption on CO_2 emissions is significantly positive.

In addition, some scholars have also examined the relationship between corruption and CO_2 emissions in different countries or regions. Using panel data from 61 countries during 2003–2016, Akhbari and Nejati (2019) found a non-linear relationship between corruption and pollution: in developing countries, a 1% drop in corruption levels reduces CO_2 emissions by 0.08%; in developed countries, the effect of corruption on CO_2 emissions is not significant. Zhang et al. (2016) analyzed the impact of corruption on CO_2 emissions in APEC member economies based on a panel quantile regression approach. The findings showed that corruption had a significant negative effect on CO_2 emissions in low-carbon-emitting countries, but no significant effect on CO_2 emissions in high-carbon-emitting countries. Rahman and Alam (2022) concluded that corruption stimulates CO_2 emissions in 47 Asian countries. Xie et al. (2023) reached the same results for 30 Chinese provinces. Differently, Sultana et al. (2022) emphasized that corruption control increases CO_2 emissions in 15 emerging economies.

In summary, the studies about the relationship between DE and CO_2 emissions can be attributed to the following aspects. The initial studies mostly focus on the linear relationship between DE and CO_2 emissions. There are differences in the conclusions reached through empirical tests. However, there is relatively little literature on such studies, which is due to the different natural resource rent and anticorruption regulation in different countries that may lead to a non-linear relationship. This study argues that the impact of DE on CO_2 emissions may change when natural resource rent and anticorruption regulation are at different levels. No study in the literature analyzes the non-linear relationship between CO_2 emissions and digitalization at the global level with large panel data. This study aims to fill this research gap for the first time for 97 countries by using a threshold model regression that includes anticorruption regulation and natural resource rent as threshold variables.

3. Methodology and data

3.1. Econometric model

This study uses a linear model as in Eq. (1) to investigate the impact of the DE on CO_2 emissions:

$$\ln CO_{2it} = \beta X + \alpha_1 dig_{it} + \mu_i + \varepsilon_{it} \tag{1}$$

where i denotes the country, t denotes the years, CO_{2it} is the CO_2 emissions in a country i in year t, dig_{it} denotes the DE index, X is the set of control variables, mainly including renewable energy consumption (ren) and trade openness (tra), and ε_{it} is the random disturbance term. To eliminate the effect of heteroskedasticity, this study takes a natural logarithmic form for some variables.

Given the differences in natural resource rent and anticorruption regulation in different countries, there may be a nonlinear relationship between digitalization and CO_2, rather than a simple linear relationship. Considering that there may be a threshold effect for the impact of DE on pollution, this paper draws on the work of Hansen (1999) to construct a panel threshold model. Take $rent_{it}$ for example, the basic idea of a single threshold is that $rent_{it}$ is used as the set threshold variable, and the model is divided into two. If the actual value of the threshold variable $rent_{it}$ is greater than h, the core explanatory variables are significantly different from the coefficients of the core explained variables when they are smaller than the threshold. In this case, the impacts of core explanatory variables on the explained variable can be nonlinear. This study analyzes the threshold effect of the DE on CO_2 emissions by considering natural resource rent and anticorruption regulation as threshold variables. The expression for the single threshold model is presented in Eq. (2). Another popular model is the double threshold represented by Eq. (3).

$$\ln CO_{2it} = \beta X + \alpha_1 dig_{it} I(rent_{it} \le h) + \alpha_2 dig_{it} I(rent_{it} > h) + \mu_i + \varepsilon_{it} \tag{2}$$

$$\ln CO_{2it} = \beta X + \alpha_1 dig_{it} I(cor_{it} \le h_1) + \alpha_2 dig_{it} I(h_1 < cor_{it} \le h_2) + \alpha_3 dig_{it} I(cor_{it} > h_2) + \mu_i + \varepsilon_{it} \tag{3}$$

where $rent_{it}$ and cor_{it} are the threshold variables. Assuming that h is the threshold value, β, α_1, and α_2 are corresponding coefficients. $I(\cdot)$

is an indicator function that corresponds to a bracketed value of 1 when the condition is met and 0 when it is not.

Prior to the formal estimation of the threshold model, a threshold effect test is first required to determine the specific value of the threshold variable h. The optimal threshold estimate h is searched for according to the principle that the value of the threshold variable has the smallest sum of squares of the residuals, satisfying as in Eq. (4):

$$\hat{h} = \operatorname{argmin} S_1(h) \tag{4}$$

where $\hat{h}$ is a consistent estimate of h, $S_1(h)$ is the residual sum of squares of the threshold regression equation, and the minimum residual sum of squares satisfies:

$$\hat{\sigma} = S_1\left(\hat{h}\right)/[m(t-1)] \tag{5}$$

In Eq. (5), m is the sample size and t is the time duration, and then it is needed to estimate the significance of the parameters and test the truth of the thresholds.

The first step is to test the significance of the parameter estimates, and this study applies the Lagrange multiplier bootstrap sampling method proposed by Hansen (1999). The study tests the existence of the threshold effect, assuming that there is a threshold effect in the threshold equation, and the corresponding null and alternative hypotheses can be expressed as in Eq. (6) and Eq. (7), respectively:

$$H_0 : \alpha_{1i} = \alpha_{2i}\,(i) = 1,2,3,4 \tag{6}$$

$$H_1 : \alpha_{1i} \neq \alpha_{2i}\,(i) = 1,2,3,4 \tag{7}$$

Eq. (8) represents the F statistic for testing the null hypothesis.

$$F = \frac{S_0 - S_1\left(\hat{h}\right)}{\hat{\sigma}^2} \tag{8}$$

The second step is to test the truthfulness of the threshold based on the uncertainty of the threshold value. The sampling bootstrap method is used to test whether the threshold regression equation has a statistically significant threshold effect in the statistical sense, i.e., by constructing its asymptotic empirical distribution to test whether the likelihood ratio expressed in Eq. (9) is satisfied by the judgment.

$$LR_1(h) = \frac{S_1(h) - S_1\left(\hat{h}\right)}{\hat{\sigma}^2} \tag{9}$$

where $S_1(h), S_1\left(\hat{\mathrm{h}}\right)$ are the residual sum of squares of the null and alternative hypothetical threshold models, respectively. According to Hansen (1999), $LR_1(h)$ obeys the asymptotic normal distribution and takes $X(\alpha) = -2\ln\left(1-\sqrt{1-\alpha}\right)$ (α is a pre-given asymptotic level) as the effective asymptotic threshold. If $LR_1(h) > X(\alpha)$, then the original hypothesis is rejected, indicating that there is a threshold effect in the above threshold regression equation.

3.2. Variable measurement

3.2.1. Core variables

This study first conducts a fixed effects test on the linear relationship of the DE affecting CO_2 emissions, followed by an examination of the nonlinear impacts of the DE over CO_2 emissions using natural resource rent and anticorruption regulation as the threshold variables. This study employs panel data for 97 countries from 2003 to 2019. The selection of each variable and the associated data sources are explained below.

The primary explanatory factor is the composite index of DE, which is constructed following existing studies (Shahbaz et al., 2022). The index includes four aspects: Infrastructure, Social Effect, Digital Business, and Social Support. The composite index is calculated using the entropy method, with the secondary indicators Telecommunications Infrastructure Index, Online Service Index, and E-participation index coming from the United Nations Economic and Social Department of Economic and Social Affairs released the e-Government survey report. In addition, this comprehensive measurement has a wide coverage, greater timeliness, and scientific evaluation of indicators. This calculation is widely used in academic research, which currently only publishes data for 2003, 2004, 2005, 2008, 2010, 2012, 2014, 2016, 2018, and 2020. Since it is discrete data are involved, this study refers to the approach of Dhaoui (2022) supplemented by panel data with linear interpolation. The specific names of the indicators, data sources, and types of indicators are listed in Table 3.

3.2.2. Threshold variables

Total natural resource rent (*rent*) is calculated as total natural resource rent as a percentage of GDP and is composed of the following elements: petroleum rents, natural gas rents, coal rents, mineral rents, and forest rents (Hassan et al., 2019). Anticorruption regulation(*cor*) is public power used for private gain and includes both small-scale and large-scale corruption. The "capture" of the state by private interests is reflected in the corruption control index, which varies from 0 to 100, with higher scores corresponding to better control of corruption (Ozturk and Al-Mulali, 2015).

3.2.3. Control variables

To lessen the influence of exogenous factors on the precise evaluation of the impact of the DE on CO_2 emissions, the ratio of renewable energy consumption (*ren*) in the total energy mix (Dong et al., 2022; Wang et al., 2023a, b, c), and trade openness (*tra*) (Wang et al., 2022b) were chosen as control variables. The degree of trade openness was measured by imported and exported

Table 3
The digital economy index's sub-index names and data sources.

Primary Index	Secondary Index	Data Source	Indicator Nature
Infrastructure	Fixed broadband subscriptions (per 100 people)	ITU (2022)	+
	Fixed telephone subscriptions (per 100 people)	ITU (2022)	+
	Mobile cellular subscriptions (per 100 people)	ITU (2022)	+
	Telecommunication Infrastructure Index	UN (2022)	+
Social effect	Individuals using the Internet (% of population)	World Bank (2022)	+
	Online Service Index	UN (2022)	+
	E-Participation Index	UN (2022)	+
	Medium and high-tech manufacturing value added (% of manufacturing value added)	World Bank (2022)	+
Digital business	ICT goods exports (% of total goods exports)	World Bank (2022)	+
	ICT goods imports (% of total goods imports)	World Bank (2022)	+
Social support	Per capita value added of service industry ($US/person)	World Bank (2022)	+

goods and services, which accounted for the share of GDP. Table 4 represents the descriptive properties for all series.

4. Empirical results and discussion

4.1. Preliminary analysis

Before checking the link between the DE and CO_2 emissions, the correlations of all variables are tested. As can be seen from Table 5, the coefficient of *dig* is 0.475, indicating a positive correlation with CO_2 emissions at the 1% significance level. The maximum value of VIF is 2.69 according to the results of the variance inflation factor, and the VIF of all variables is less than 5. Moreover, most of the correlation coefficients are less than 0.8. Combining the analysis results of the correlation coefficient and variance inflation factor indicates that there is no multicollinearity problem.

4.2. Benchmark regression analysis

To draw more accurate conclusions, it is necessary to use mixed regression, fixed-effect, and random-effect approaches to uncover the quantitative relationship between the variables, and the LM test and Hausman test to choose the appropriate model, through the test can be obtained, should choose the fixed effect model.

The panel regression findings demonstrate that the DE has an important linear impact on CO_2 emissions. This effect may have different characteristics because some variables are in different intervals, and the variables have a nonlinear relationship with one another. The panel threshold regression is used to test whether there is a nonlinear relationship between DE and CO_2 by using natural resource rent and anticorruption regulation as threshold variables (See Table 6).

4.3. Threshold model analysis

The smoothness of the variables is the basis for the regression test. If the variables are not smooth, it may lead to pseudo regression, so it is necessary to perform unit root tests for all variables before performing the threshold regression test. Since the panel data type used in this study is a short panel, the unit root test of Harris and Tzavalis (1999) is used, and through the test, it can be determined that all variables have smoothness (To save space, the results of the unit root test are not shown. The results can be provided by the corresponding author upon request.).

4.3.1. Check the validity of the threshold effect

This study employed Stata 17 for empirical analyses, and after 300 iterations of the sample, the existence of the threshold effect was examined.

According to Table 7, all threshold variables passed the existing test, natural resource rent was at a 10% level with a single threshold, and anticorruption regulation was at a 5% level with a double threshold.

4.3.2. Threshold regression outcomes

To further test whether the threshold estimates are true values and to determine the confidence intervals of the thresholds, this study separately plots the trend graphs of the likelihood ratio (LR) with natural resource rent and anticorruption regulation as the threshold variables. Table 8 shows the threshold estimates with the confidence intervals.

The trend graphs can be used to better assess the thresholds and corresponding confidence intervals. In Fig. 1, the 95% confidence value of 7.35 is the dashed line parallel to the x-axis, and the estimated threshold value ensures the minimum value of the LR function when natural resource rent and anticorruption regulation are used as threshold variables.

Fig. 2 indicates that natural resource rent originally showed an upward trend, but recently has declined rapidly. Table 8 shows that the natural resource rent had a single threshold value of 16.5067 and the overall trend changed from positive promotion to significant negative inhibition at a 10% level. When the threshold variable $rent \leq 16.5067$, the estimated coefficient of the DE was 0.800, which was significant at the 1% level. When the threshold variable $rent > 16.5067$, the estimated coefficient of the DE was -1.629, which was significant at the 5% level.

This tendency may be because a low rent for natural resources mainly indicates that the resources are sufficient and abundant. To drive social development and technological progress, people need to exploit more natural resources at this stage. Decision makers take the production decision of ICT companies as an example, where D and MR represent the demand curve and the marginal revenue curve of the company (Fig. 3).

There are D = MR, MPC, and MSC stand for entrepreneurial marginal cost and social marginal cost. Natural resources have a negative externality, MPC > MSC, which means that part of the costs incurred by the enterprise must be borne by society, and the marginal external cost MEC represents the difference between the marginal social cost and the marginal cost of the enterprise as the vertical distance between the two lines. When resources are abundant and exploitation is unconstrained, the maximum return the firm can earn is Q_2, but at this point, the socially optimal yield is Q_1, and the yield determined according to the principle of maximizing social utility is smaller than the yield determined according to the principle of maximizing enterprise profits. In this case, natural resources are overexploited, too many pollutants are emitted, and CO_2 emissions increase. However, with the decline of resources and the rise of natural resource rent, people are gradually realizing the importance of using resources rationally. If the natural resource rent continues to rise above the threshold, the rapid integration and development of the DE will bring great changes to production and consumption. The introduction of data elements and digital technology into all production processes under the DE can improve the overall environmental performance of industrial production, including raw material extraction and handling, delivery, manufacturing, distribution, and waste management. This can reduce dependence on natural resources by promoting reduction, reuse, and recycling, and further development of

Table 4
Descriptive statistics.

Variable	Obs	Mean	Std Dev	Minimum	Maximum
lnCO_2	1,649	10.42	2.100	5.010	16.19
dig	1,649	0.25	0.17	0.01	0.78
ren	1,649	29.3	26.14	0.01	96.04
tra	1,649	82.47	54.15	0	380.1
rent	1,649	4.18	6.76	0	55.48
cor	1,649	54.69	27.38	1.420	100

Note: Obs—Observation; Std Dev—Standard Deviation.

Table 5
Results of the correlation matrix.

	$lnCO_2$	*dig*	*ren*	*tra*	*rent*	*cor*	VIF
$lnCO_2$	1.00						
dig	0.475***	1.00					2.69
ren	−0.527***	−0.529***	1.00				1.42
tra	−0.086***	0.411***	−0.305***	1.00			1.23
rent	0.033	−0.332***	0.118***	−0.207***	1.00		1.16
cor	0.182***	0.741***	−0.419***	0.347***	−0.340***	1.00	2.28

Note: *** represents significance at the 1% level.

Table 6
Results of fixed effects regression.

Variable	coefficient
dig	0.751***
	(0.1891)
ren	−0.0293***
	(0.0025)
tra	−0.00638***
	(0.0007)
cons	11.61***
	(0.1050)
N	1,649

Note: *** represents significance at the 1% level.

green, energy-saving technologies can significantly reduce CO_2 emissions.

Fig. 4 represents the anticorruption regulation and the 95% confidence interval. The figure shows that the LR statistics are above the confidence interval for the entire period, except for one small deviation.

The results in Table 8 also indicate that the thresholds for anticorruption regulation are 8.7805 and 10.0962. The overall trend changed from positive promotion to weak promotion, and the regression coefficient was statistically significant at the 5% level.

When the threshold variable $cor \leq 8.7805$, the regression coefficient was significantly positive at the 10% level, and when the threshold variable was between $8.7805 < cor \leq 10.0962$, it accelerated the positive effect of the DE on CO_2 emissions, indicating that in the process of transforming traditional industries into the DE there is a ranking of priorities: First, the industries that need urgent transformation, such as industries with high pollution, high emissions, and high consumption, need to adopt digital technology earlier to improve production capacity. The adoption and promotion of digital technology will greatly increase the production capacity of these industries, enhance the energy demand, and lead to a sharp increase in total CO_2 emissions (Li et al., 2021b), at this time, the impact of anticorruption regulation is less.

When the threshold variable $cor > 10.0962$ is at the 1% significance level, the beneficial promotion effect becomes smaller. With the popularity of the DE, it is promoted and applied throughout the industry. Digital industrialization and the digitalization of industry are on the rise, and the dividend effect of DE on the ecological environment is gradually coming to the fore. At a time when heavily polluting enterprises are trying to negatively affect environmental quality by bribing environmental authorities and influencing environmental policies. The government will strengthen anticorruption regulation to cut off the political connections of enterprises and force them to lean towards clean industries with high output and low emissions through technological innovation to slow down the rise of CO_2 emissions.

Fig. 5 shows the double threshold for anticorruption regulation. It can be seen that anticorruption regulation has an increasing trend at the first threshold 8.7805 and the second threshold 10.0962.

According to the estimation of the threshold value of *rent* and *cor*, the obtained model regression results are presented in Table 9.

Among the control variables, renewable energy consumption contributes the most to CO_2 reduction, decreasing by 0.0291% per 1% increase, which is consistent with the reality of development. On the one hand, renewable energy, as a green, low-carbon energy source, is crucial for sustainable economic and social growth, environmental protection, climate change mitigation, and energy system improvement; on the other hand, the use of renewable energy also indirectly affects electricity consumption, thus reducing CO_2 emissions. Second, trade openness, for every 1% increase, CO_2 emissions decrease by 0.00602%. In general, both contribute to reducing CO_2 emissions (Li et al., 2021c).

5. Robustness check

To robustly test the threshold effect of DE on CO_2 emissions, this study uses two methods. First, one control variable is removed from each panel threshold model for regression analysis, and second, electricity power supply and economic growth are used as proxies for renewable energy consumption and trade openness.

5.1. Remove the control variables

One by one, one control variable is removed from the panel threshold model. *ren* and *tra* are removed from the panel threshold model for regression analysis, and the outcomes are displayed in Table 10.

Table 10 shows that there is still a one-threshold effect of the DE on CO_2 emissions, with no change in the threshold and the coefficients having the same direction when natural resource rent is used as the threshold variable. The same is true when anticorrup-

Table 7
Test of the threshold effect.

Threshold Variable	Threshold number	*F* value	*p* value	10%	5%	1%
rent	Single	26.48	0.070*	22.2616	30.2904	48.0331
cor	Single	43.11	0.0267**	34.2095	38.7805	46.9905
	Double	65.02	0.0233**	46.3415	53.8194	71.8977

Note: **, and * represent significance at the 5%, and 10% levels, respectively.

Table 8
Threshold estimates and confidence intervals.

Threshold Variables	Test Model	Threshold Value	95% Confidence Interval
rent	Single threshold	16.5067	(15.8300, 17.1278)
cor	Single threshold	8.7805	(8.1731, 11.3744)
	Double threshold	10.0962	(9.6154, 10.4762)

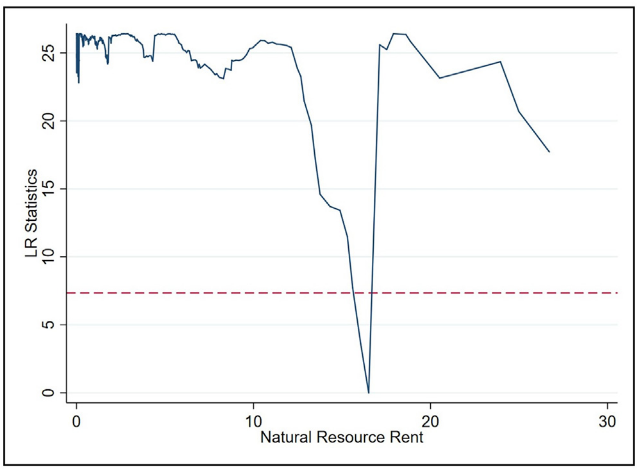

Fig. 1. Natural resource rent threshold estimates and confidence intervals. The figure presents estimated LR statistics with confidence intervals for natural resources.

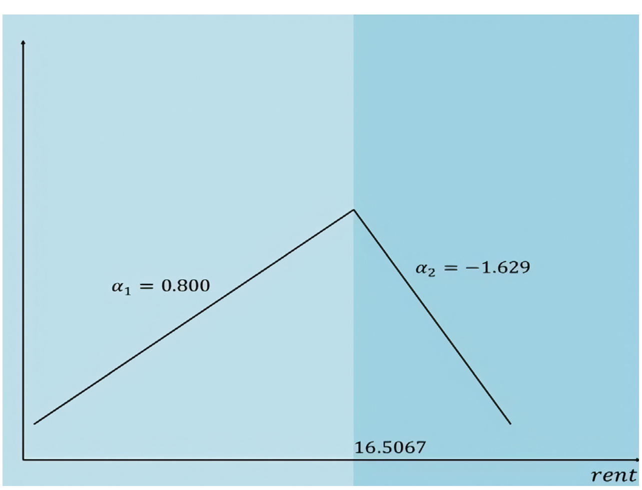

Fig. 2. Change of the natural resource rent level in the world. The slope parameters α_1 and α_2 denote the scale effect level.

tion regulation is used as a threshold variable, so the model is robust.

5.2. Replace the control variables

It is chosen to replace the two control variables in the baseline regression with electricity power supply level and economic growth. The fact that the results in Table 11 matched those in the benchmark regression suggests that they are reliable.

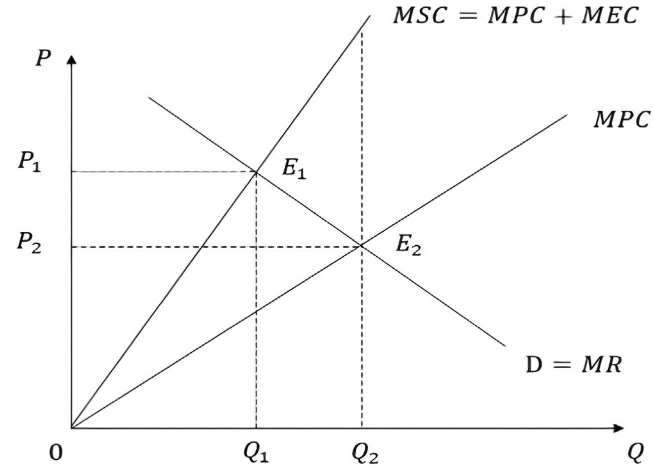

Fig. 3. Production decisions of ICT companies. The figure shows the production decisions of ICT firms at two different price levels corresponding to marginal revenue and marginal cost.

6. Conclusions and implications

Considering the empirical examination results, this study distills and summarizes the findings of the inquiry and proposes policy implications for each country to achieve CO_2 reduction as a reference.

This study sets a panel threshold regression model to empirically test the effect of the DE on CO_2 emissions, using natural resource rent and anticorruption regulation as threshold variables. The results highlight that the DE has a single threshold effect on CO_2 emissions when natural resource rent is used as the threshold variable and that there is an inverted U-shaped relationship between the DE and CO_2 emissions. The facilitating and inhibiting effects are significant in both intervals. When anticorruption regulation is used as a threshold, the DE overall promotes the growth of CO_2 emissions, and there is a double threshold effect showing that the promoting effect of the DE on CO_2 emissions increases and then decreases as the level of anticorruption regulation increases.

In light of the above-mentioned empirical findings, this study makes some recommendations. Formulate a DE development strategy suitable for the country and fully play a critical function of the DE in the reduction of CO_2 emissions. Due to the threshold effect of natural resource rent, the DE has different degrees of impact on CO_2 emissions. Hence, it is necessary to propose a development strategy for DE, which is suitable for the country, by considering the nation's economic expansion, renewable energy consumption, natural resource exploitation and utilization, foreign direct investment, etc., and guide the ICT industry to focus on environmentally friendly and low-carbon industries to realize the upgrading of national industrial structure.

As a policy recommendation, governments must priorities the Internet economy as it unleashes low-carbon technologies. Policymakers must promote the comprehensive integration of the DE into conventional industries, vigorously support the development of clean technologies and clean energy, achieve green development, and strengthen efforts to support key projects in noncommodity-based industries. They should also establish mechanisms for the growth of non-resource-based sectors, and gradually reduce overdependence on resources by accelerating the expansion of industrial chains, vigorously developing successor industries, and cultivating new advantageous industries. Natural resources are also an important production factor. Therefore, governments should adopt a prudent and transparent management approach to strengthen the management of resource rents, pro-

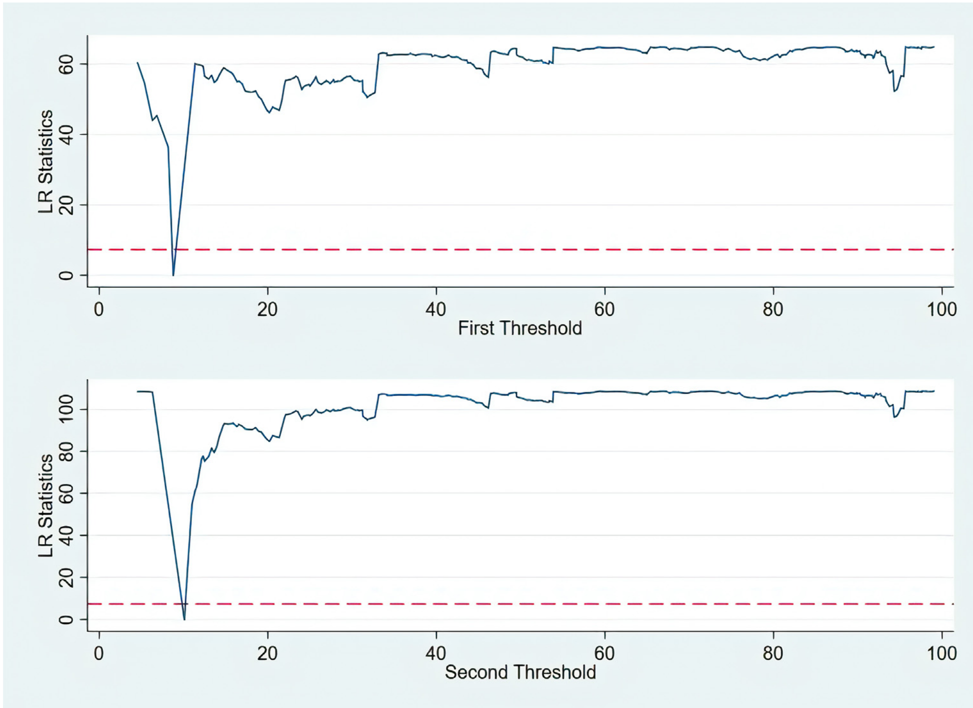

Fig. 4. Anticorruption regulation threshold estimates and confidence intervals. The figure presents estimated LR statistics with confidence intervals for anticorruption regulation.

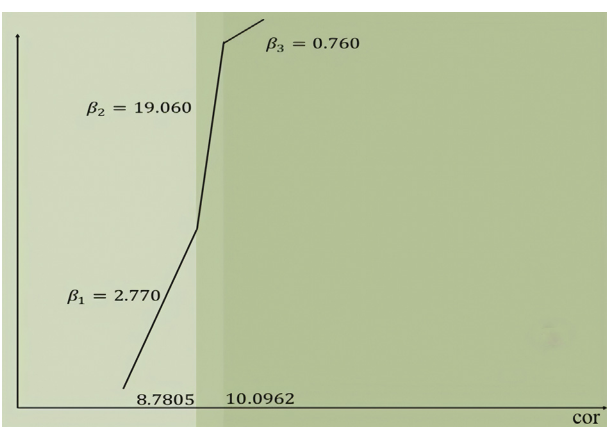

Fig. 5. Change of anticorruption regulation in the world. The slope parameters β_1, β_2 and β_3 denote the scale effect level.

Table 9
Results of threshold model regression.

Variable	(1) rent	(2) cor
ren	−0.0291***	−0.0288***
	(0.0024)	(0.0024)
tra	−0.00602***	−0.00579***
	(0.0007)	(0.0007)
$\boldsymbol{dig}(\boldsymbol{q} \leq \boldsymbol{h}_1)$	0.800***	2.770*
	(0.1879)	(1.3287)
$\boldsymbol{dig}(\boldsymbol{h}_1 < \boldsymbol{q} \leq \boldsymbol{h}_2)$		19.06***
		(1.7604)
$\boldsymbol{dig}(\boldsymbol{q} > \boldsymbol{h}_2)$	−1.629**	0.760***
	(0.5142)	(0.1830)
cons	11.58***	11.54***
	(0.1044)	(0.1018)
N	1,649	1,649

Note: *: p < 0.1; **: p < 0.05; ***: p < 0.01.

mote the development of related industries through supportive measures, cultivate beneficial industries, and realize the resource gospel.

The stock of the nation's natural resources should be fully considered in DE development. It is recommended that CO_2 emissions and the environment be included in the performance assessment criteria and that an audit system based on emissions reduction be established. Because natural resource rent affects the relationship of the DE with CO_2 emissions by causing a threshold effect, the development of each country should coordinate the relationship between the DE, environmental governance, and natural resources. When natural resource rents are low, the idea that resources are inexhaustible should not exist, and governments need to improve the regulatory system for natural resource use and protection. Governments can also formulate environmental regulatory policies suitable for their countries because good environmental regulatory policies will not only increase the accessible cost of resources and weaken the preference of enterprises to consume resource products, but also limit the emissions of carbon-intensive industries. In other words, the DE tends to develop environmentally friendly industries. When natural resource rents are high, the DE should benefit from advantages by supporting the penetration and integration of digital technology and energy development technology, stimulating the promotion and transformation of energy-saving technology, promoting green development, and reducing energy consumption. Meanwhile, the substitution effect brought by digital technology is crucial to reducing CO_2 emissions.

Governments should further strengthen their anti-corruption efforts in environmental regulation and actively seek appropriate anti-corruption models for their countries to thoroughly curb CO_2 emissions at the source and promote economic development. Anti-corruption has cut the political ties of enterprises and forced

Table 10
Remove the Control Variables.

Variable	*rent*		*cor*	
	Remove *tra*	Remove *ren*	Remove *tra*	Remove *ren*
ren	−0.0319***		−0.0314***	
	(0.0025)		(0.0024)	
tra		−0.00628		−0.00695***
		(0.0033)		(0.0007)
$\boldsymbol{dig}(\boldsymbol{q} \le \boldsymbol{h}_1)$	0.834***	1.193***	2.369	3.288*
	(0.1919)	(0.2008)	(1.3559)	(1.3893)
$\boldsymbol{dig}(\boldsymbol{h}_1 < \boldsymbol{q} \le \boldsymbol{h}_2)$			20.18***	19.87***
			(1.7922)	(1.8403)
$\boldsymbol{dig}(\boldsymbol{q} > \boldsymbol{h}_2)$	−1.995***	−1.746**	0.783***	1.116***
	(0.5234)	(0.5501)	(0.1868)	(0.1889)
cons	11.16***	10.16***	11.13***	10.70***
	(0.0932)	(0.0535)	(0.0909)	(0.0785)
N	1,649	1,649	1,649	1,649

Note: *: $p < 0.1$; *: $p < 0.05$; ***: $p < 0.01$.

Table 11
Replace the Control Variables.

Variable	(1) *rent*	(2) *cor*
ele	0.0260***	0.0238***
	(0.0020)	(0.0019)
ggr	−0.00618*	−0.00695*
	(0.0031)	(0.0030)
$\boldsymbol{dig}(\boldsymbol{q} \le \boldsymbol{h}_1)$	0.577**	2.178
	(0.1961)	(1.3647)
$\boldsymbol{dig}(\boldsymbol{h}_1 < \boldsymbol{q} \le \boldsymbol{h}_2)$		17.92***
		(1.8201)
$\boldsymbol{dig}(\boldsymbol{q} > \boldsymbol{h}_2)$	−2.250***	0.567**
	(0.5231)	(0.1923)
cons	8.075***	8.239***
	(0.1662)	(0.1641)
N	1,649	1,649

Note: *: $p < 0.1$; **: $p < 0.05$; ***: $p < 0.01$.

enterprises to improve their technological level and core competitiveness through innovation, thereby enhancing environmental quality. Therefore, anti-corruption actions in the field of environmental protection should not only be adhered to but also be strengthened. At the same time, regions and countries that are largely dependent on manufacturing industries, especially polluting industries, can use digital technology to change their industrial structure toward low energy consumption, attract technology-intensive industries, and invest in new energy industries to reduce emissions and save energy.

Finally, since this study focuses mainly on the association of DE with CO_2 emissions, this can be considered a limitation. Considering this, future studies can research the association of the digital economy with various environmental indicators, such as the ecological footprint or the load capacity factor. Thus, the validity of the empirical results can be checked by using other environmental indicators. In addition, future studies can examine the threshold effects for other countries and groups of countries using other novel econometric approaches. In this way, the existing literature can be substantially enriched.

CRediT authorship contribution statement

Qiang Wang: Conceptualization, Methodology, Software, Data curation, Writing – original draft, Supervision, Writing – review & editing. **Jiayi Sun:** Methodology, Data curation, Investigation, Writing – original draft, Writing – review & editing. **Ugur Korkut Pata:** Methodology, Software, Data curation, Investigation, Writing – original draft, Writing – review & editing. **Rongrong Li:** Methodology, Data curation, Investigation, Writing – original draft. **Mustafa Tevfik Kartal:** Data curation, Investigation, Writing – original draft.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgement

This work is supported by National Natural Science Foundation of China (Grant No. 72104246).

References

Abeydeera, L.H.U.W., Mesthrige, J.W., Samarasinghalage, T.I., 2019. Global research on carbon emissions: A scientometric review. Sustainability 11 (14), 3972. https://doi.org/10.3390/su11143972.
Acheampong, A.O., 2018. Economic growth, CO_2 emissions and energy consumption: what causes what and where? Energy Econ. 74, 677–692. https://doi.org/10.1016/j.eneco.2018.07.022.
Adebayo, T. S., Pata, U. K., Akadiri, S. S. 2022. A comparison of CO_2 emissions, load capacity factor, and ecological footprint for Thailand's environmental sustainability. Environ. Develop. Sustain. doi: 10.1007/s10668-022-02810-9.
Adebayo, T.S., Ullah, S., Kartal, M.T., Ali, K., Pata, U.K., Ağa, M., 2023. Endorsing sustainable development in BRICS: The role of technological innovation and renewable energy consumption, and natural resources in limiting carbon emission. Sci. Total Environ. 859, 160181. https://doi.org/10.1016/j.scitotenv.2022.160181.
Agboola, M.O., Bekun, F.V., Joshua, U., 2021. Pathway to environmental sustainability: Nexus between economic growth, energy consumption, CO_2 emission, oil rent and total natural resources rent in Saudi Arabia. Resour. Pol. 74, 102380. https://doi.org/10.1016/j.resourpol.2021.102380.
Akhbari, R., Nejati, M., 2019. The effect of corruption on carbon emissions in developed and developing countries: Empirical investigation of a claim. Heliyon 5 (9), e02516. https://doi.org/10.1016/j.heliyon.2019.e02516.
Bekun, F.V., Alola, A.A., Sarkodie, S.A., 2019. Toward a sustainable environment: Nexus between CO_2 emissions, resource rent, renewable and nonrenewable energy in 16-EU countries. Sci. Total Environ. 657, 1023–1029. https://doi.org/10.1016/j.scitotenv.2018.12.104.
British Petroleum, 2022. Statistical Review of World Energy 2022 | 71st edition. https://www.bp.com/content/dam/bp/business-sites/en/global/corporate/pdfs/energy-economics/statistical-review/bp-stats-review-2022-full-report.pdf (accessed 14 December 2022).
Caglar, A.E., Zafar, M.W., Bekun, F.V., Mert, M., 2022. Determinants of CO_2 emissions in the BRICS economies: The role of partnerships investment in energy and economic complexity. Sustain. Energy. Technol. 51, 101907. https://doi.org/10.1016/j.seta.2021.101907.
Carlsson, B., 2004. The Digital Economy: what is new and what is not? Struct. Chang. Econ. Dyn. 15 (3), 245–264. https://doi.org/10.1016/j.strueco.2004.02.001.

Chen, Y., 2020. Improving market performance in the digital economy. Ch. Econ. Rev. 62, 101482. https://doi.org/10.1016/j.chieco.2020.101482.

Chen, L., 2022a. How CO_2 emissions respond to changes in government size and level of digitalization? Evidence from the BRICS countries. Environ. Sci. Pollut. Res. 29 (1), 457–467. https://doi.org/10.1007/s11356-021-15693-6.

Chen, P., 2022b. Relationship between the digital economy, resource allocation and corporate carbon emission intensity: New evidence from listed Chinese companies. Environ. Res. Com. 4 (7), 075005. https://doi.org/10.1088/2515-7620/ac7ea3.

Cole, M.A., 2007. Corruption, income and the environment: An empirical analysis. Ecol. Econ. 62 (3–4), 637–647. https://doi.org/10.1016/j.ecolecon.2006.08.003.

Danish, Baloch, M. A., Mahmood, N., Zhang, J. W. 2019. Effect of natural resources, renewable energy and economic development on CO_2 emissions in BRICS countries. Sci. Total Environ. 678, 632-638. doi: 10.1016/j.scitotenv.2019.05.028.

Deacon, R.T., Mueller, B., 2006. Political economy and natural resource use. In: Ramón, L.M., Toman, M. (Eds.), Economic Development and Environmental Sustainability. Oxford University Press, pp. 122–153. https://doi.org/10.1093/0199298009.003.0005.

Dhaoui, I., 2022. E-government for sustainable development: Evidence from MENA countries. J. Knowl. Econ. 13 (3), 2070–2099. https://doi.org/10.1007/s13132-021-00791-0.

Dogan, A., Pata, U.K., 2022. The role of ICT, R&D spending and renewable energy consumption on environmental quality: Testing the LCC hypothesis for G7 countries. J. Clean. Prod. 380, 135038. https://doi.org/10.1016/j.jclepro.2022.135038.

Dong, F., Hu, M., Gao, Y., Liu, Y., Zhu, J., Pan, Y., 2022. How does digital economy affect carbon emissions? Evidence from global 60 countries. Sci. Total Environ. 852, 158401. https://doi.org/10.1016/j.scitotenv.2022.158401.

Ganda, F., 2020. The influence of corruption on environmental sustainability in the developing economies of Southern Africa. Heliyon 6 (7), e04387. https://doi.org/10.1016/j.heliyon.2020.e04387.

Grossman, G.M., Krueger, A.B., 1991. Environmental impacts of A north American free trade agreement. National Bureau of Economic Research Working Paper, No. 3914.

Hansen, B.E., 1999. Threshold effects in non-dynamic panels: Estimation, testing, and inference. J. Econ. 93 (2), 345–368. https://doi.org/10.1016/S0304-4076(99)00025-1.

Harris, R.D., Tzavalis, E., 1999. Inference for unit roots in dynamic panels where the time dimension is fixed. J. Econ. 91 (2), 201–226. https://doi.org/10.1016/S0304-4076(98)00076-1.

Hassan, S.T., Xia, E., Khan, N.H., Shah, S.M.A., 2019. Economic growth, natural resources, and ecological footprints: Evidence from Pakistan. Environ. Sci. Pollut. Res. 26 (3), 2929–2938. https://doi.org/10.1007/s11356-018-3803-3.

Huang, S.Z., Sadiq, M., Chien, F., 2021. The impact of natural resource rent, financial development, and urbanization on carbon emission. Environ. Sci. Pollut. Res. https://doi.org/10.1007/s11356-021-16818-7.

ITU. 2022. Statistics. https://www.itu.int/en/ITU-D/Statistics/Pages/stat/default.aspx (accessed 16 December 2022).

Jiang, X., 2020. Digital economy in the post-pandemic era. J. Chin. Econ. Bus. Stud. 18 (4), 333–339. https://doi.org/10.1080/14765284.2020.1855066.

Joshua, U., Bekun, F.V., 2020. The path to achieving environmental sustainability in South Africa: The role of coal consumption, economic expansion, pollutant emission, and total natural resources rent. Environ. Sci. Pollut. Res. 27 (9), 9435–9443. https://doi.org/10.1007/s11356-019-07546-0.

Kolstad, I., Søreide, T., 2009. Corruption in natural resource management: Implications for policy makers. Resour. Pol. 34 (4), 214–226. https://doi.org/10.1016/j.resourpol.2009.05.001.

Kong, S., Wu, Y., Wang, X., Cui, W., 2022. Impact of digital economy development on carbon emissions an empirical study based on 15 RCEP Countries. J. Algeb. Stat. 13 (3), 3776–3791.

Lee, C.C., Yuan, Y., Wen, H., 2022. Can digital economy alleviate CO_2 emissions in the transport sector? Evidence from provincial panel data in China. Nat. Resour. Forum 46 (3), 289–310. https://doi.org/10.1111/1477-8947.12258.

Li, Y., Alharthi, M., Ahmad, I., Hanif, I., Hassan, M.U., 2022. Nexus between renewable energy, natural resources and carbon emissions under the shadow of transboundary trade relationship from South East Asian economies. Energy Strategy Rev. 41, 100855. https://doi.org/10.1016/j.esr.2022.100855.

Li, K., Kim, D.J., Lang, K.R., Kauffman, R.J., Naldi, M., 2020. How should we understand the digital economy in Asia? Critical assessment and research agenda. Electron. Commer. Res. Appl. 44, 101004. https://doi.org/10.1016/j.elerap.2020.101004.

Li, X., Liu, J., Ni, P., 2021c. The impact of the digital economy on CO_2 emissions: A theoretical and empirical analysis. Sustainability 13 (13), 7267. https://doi.org/10.3390/su13137267.

Li, R., Wang, Q., Liu, Y., Jiang, R., 2021a. Per-capita carbon emissions in 147 countries: The effect of economic, energy, social, and trade structural changes. Sustain Prod. Consump. 27, 1149–1164. https://doi.org/10.1016/j.spc.2021.02.03.

Li, Z., Wang, J., 2022. The dynamic impact of digital economy on carbon emission reduction: evidence city-level empirical data in China. J. Clean. Prod. 351, 131570. https://doi.org/10.1016/j.jclepro.2022.131570.

Li, Y., Yang, X., Ran, Q., Wu, H., Irfan, M., Ahmad, M., 2021b. Energy structure, digital economy, and carbon emissions: Evidence from China. Environ. Sci. Pollut. Res. 28 (45), 64606–64629. https://doi.org/10.1007/s11356-021-15304-4.

Ma, Q., Tariq, M., Mahmood, H., Khan, Z., 2022. The nexus between digital economy and carbon dioxide emissions in China: The moderating role of investments in research and development. Technol. Soc. 68, 101910. https://doi.org/10.1016/j.techsoc.2022.101910.

Moriset, B., Malecki, E.J., 2009. Organization versus space: The paradoxical geographies of the digital economy. Geography Compass 3 (1), 256–274. https://doi.org/10.1111/j.1749-8198.2008.00203.x.

Murshed, M., 2020. An empirical analysis of the non-linear impacts of ICT-trade openness on renewable energy transition, energy efficiency, clean cooking fuel access and environmental sustainability in South Asia. Environ. Sci. Pollut. Res. 27 (29), 36254–36281. https://doi.org/10.1007/s11356-020-09497-3.

Nwani, C., Adams, S., 2021. Environmental cost of natural resource rents based on production and consumption inventories of carbon emissions: assessing the role of institutional quality. Resour. Pol. 74, 102282. https://doi.org/10.1016/j.resourpol.2021.102282.

OECD, 2015. Working party on communication infrastructures and services policy wireless market structures and network sharing. https://www.oecd.org/officialdocuments/publicdisplaydocumentpdf/?cote=DSTI/ICCP/CISP(2014)2/FINAL&docLanguage=En (accessed 14 December 2022).

Ozturk, I., Al-Mulali, U., 2015. Investigating the validity of the environmental Kuznets curve hypothesis in Cambodia. Ecol. Indic. 57, 324–330. https://doi.org/10.1016/j.ecolind.2015.05.018.

Pata, U.K., 2018. Renewable energy consumption, urbanization, financial development, income and CO_2 emissions in Turkey: testing EKC hypothesis with structural breaks. J. Clean. Prod. 187, 770–779. https://doi.org/10.1016/j.jclepro.2018.03.236.

Pellegrini, L., Gerlagh, R., 2006. Corruption and environmental policies: What are the implications for the enlarged EU? Eur. Environ. 16 (3), 139–154. https://doi.org/10.1002/eet.414.

Piao, X., Cui, X., 2020. Assessing China's digital economy and environmental sustainability: A regional low-carbon. Perspective. https://doi.org/10.5194/egusphere-egu2020-12740.

Rahman, M.M., Alam, K., 2022. Effects of corruption, technological innovation, globalisation, and renewable energy on carbon emissions in Asian countries. Util. Pol. 79, 101448. https://doi.org/10.1016/j.jup.2022.101448.

Safdar, S., Khan, A., Andlib, Z., 2022. Impact of good governance and natural resource rent on economic and environmental sustainability: An empirical analysis for South Asian economies. Environ. Sci. Pollut. Res. https://doi.org/10.1007/s11356-022-21401-9.

Salahuddin, M., Alam, K., 2015. Internet usage, electricity consumption and economic growth in Australia: A time series evidence. Telematics Inf. 32 (4), 862–878. https://doi.org/10.1016/j.tele.2015.04.011.

Sekrafi, H., Sghaier, A., 2018. The effect of corruption on carbon dioxide emissions and energy consumption in Tunisia. PSU Res. Rev. 2 (1), 81–95. https://doi.org/10.1108/PRR-11-2016-0008.

Shahbaz, M., Wang, J., Dong, K., Zhao, J., 2022. The impact of digital economy on energy transition across the globe: The mediating role of government governance. Renew. Sustain. Energy Rev. 166, 112620. https://doi.org/10.1016/j.rser.2022.112620.

Shen, Y., Su, Z.-W., Malik, M.Y., Umar, M., Khan, Z., Khan, M., 2021. Does green investment, financial development and natural resources rent limit carbon emissions? A provincial panel analysis of China. Sci. Total Environ. 755, 142538. https://doi.org/10.1016/j.scitotenv.2020.142538.

Sicen, L., Khan, A., Kakar, A., 2022. The role of disaggregated level natural resources rents in economic growth and environmental degradation of BRICS economies. Biophys. Econ. Sustain. 7 (3), 1–14. https://doi.org/10.1007/s41247-022-00102-4.

Sinha, A., Gupta, M., Shahbaz, M., Sengupta, T., 2019. Impact of corruption in public sector on environmental quality: Implications for sustainability in BRICS and next 11 countries. J. Clean. Prod. 232, 1379–1393. https://doi.org/10.1016/j.jclepro.2019.06.066.

Sultana, N., Rahman, M.M., Khanam, R., Kabir, Z., 2022. Environmental quality and its nexus with informal economy, corruption control, energy use, and socioeconomic aspects: the perspective of emerging economies. Heliyon 8 (6), e09569. https://doi.org/10.1016/j.heliyon.2022.e09569.

Tufail, M., Song, L., Adebayo, T.S., Kirikkaleli, D., Khan, S., 2021. Do fiscal decentralization and natural resources rent curb carbon emissions? Evidence from developed countries. Environ. Sci. Pollut. Res. 28 (35), 49179–49190. https://doi.org/10.1007/s11356-021-13865-y.

Ulucak, R., Danish, K., Ozcan, B., 2020. Relationship between energy consumption and environmental sustainability in OECD countries: the role of natural resources rents. Resour. Pol. 69, 101803. https://doi.org/10.1016/j.resourpol.2020.101803.

UN. 2022. E-Government Survey 2022: The Future of Digital Government. https://desapublications.un.org/sites/default/files/publications/2022-09/Web%20version%20E-Government%202022.pdf (accessed 16 December 2022).

Usman, A., Ozturk, I., Ullah, S., Hassan, A., 2021. Does ICT have symmetric or asymmetric effects on CO_2 emissions? Evidence from selected Asian economies. Technol. Soc. 67, 101692. https://doi.org/10.1016/j.techsoc.2021.101692.

Van Der Gaag, M., Snijders, T. A., 2003. A comparison of measures for individual social capital. In conference Creation and returns of Social Capital (pp. 30-31).

Wang, J., Luo, X., Zhu, J., 2022a. Does the digital economy contribute to carbon emissions reduction? A city-level spatial analysis in China. Chin. J. Popul. Resour. Environ. 20 (2), 105–114. https://doi.org/10.1016/j.cjpre.2022.06.001.

Wang, L., Vo, X.V., Shahbaz, M., Ak, A., 2020. Globalization and carbon emissions: is there any role of agriculture value-added, financial development, and natural resource rent in the aftermath of COP21? J. Environ. Manage. 268, 110712. https://doi.org/10.1016/j.jenvman.2020.110712.

Wang, Q., Wang, X., Li, R., 2022b. Does urbanization redefine the environmental Kuznets curve? An empirical analysis of 134 Countries. Sustain. Cities Soc. 76, 103382. https://doi.org/10.1016/j.scs.2021.103382.

Wang, Q., Wang, L., Li, R., 2023a. Trade protectionism jeopardizes carbon neutrality – Decoupling and breakpoints roles of trade openness. Sustain. Prod. Consumpt. 35, 201–215. https://doi.org/10.1016/j.spc.2022.08.034.

Wang, Q., Yang, T., Li, R., 2023b. Does income inequality reshape the environmental Kuznets curve (EKC) hypothesis? A nonlinear panel data analysis. Environ. Res. 216, 114575. https://doi.org/10.1016/j.envres.2022.114575.

Wang, Q., Zhang, F., Li, R., 2023c. Revisiting the environmental Kuznets curve hypothesis in 208 counties: The roles of trade openness, human capital, renewable energy and natural resource rent. Environ. Res. 216, 114637. https://doi.org/10.1016/j.envres.2022.114637.

World Bank, 2022. World development indicators accessed 16 December 2022 https://databank.worldbank.org/source/world-development-indicators,

Wu, Y., Shen, J., Zhang, X., Skitmore, M., Lu, W., 2016. The impact of urbanization on carbon emissions in developing countries: a Chinese study based on the U-Kaya method. J. Clean. Prod. 135, 589–603. https://doi.org/10.1016/j.jclepro.2016.06.121.

Xiang, X., Yang, G., Sun, H., 2022. The impact of the digital economy on low-carbon, inclusive growth: promoting or restraining. Sustainability 14 (12), 7187. https://doi.org/10.3390/su14127187.

Xie, G., Cui, Z., Ren, S., Li, K., 2023. Pathways to carbon neutrality: how do government corruption and resource misallocation affect carbon emissions? Environ. Sci. Pollut. R. 1–15. https://doi.org/10.1007/s11356-023-25179-2.

Zhang, L., Godil, D.I., Bibi, M., Khan, M.K., Sarwat, S., Anser, M.K., 2021. Caring for the environment: How human capital, natural resources, and economic growth interact with environmental degradation in Pakistan? A dynamic ARDL approach. Sci. Total Environ. 774, 145553. https://doi.org/10.1016/j.scitotenv.2021.145553.

Zhang, Y.-J., Jin, Y.-L., Chevallier, J., Shen, B., 2016. The effect of corruption on carbon dioxide emissions in APEC countries: A panel quantile regression analysis. Technol. Soc. 112, 220–227. https://doi.org/10.1016/j.techfore.2016.05.027.

Zhang, Y., Khan, I., Zafar, M.W., 2022c. Assessing environmental quality through natural resources, energy resources, and tax revenues. Environ. Sci. Pollut. Res. https://doi.org/10.1007/s11356-022-22005-z.

Zhang, J., Lyu, Y., Li, Y., Geng, Y., 2022a. Digital economy: An innovation driving factor for low-carbon development. Environ. Impact Assess. Rev. 96, 106821. https://doi.org/10.1016/j.eiar.2022.106821.

Zhang, J., Li, J., Ye, D., Sun, C., 2022b. The impact of digital economy of resource-based city on carbon emissions trading by blockchain technology. Comput. Intell. Neurosci. https://doi.org/10.1155/2022/6366061.