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CAN DEVELOPMENT IN THE DIGITAL ECONOMY LEAD TO A WIN-WIN FOR ‘EFFICIENCY PROMOTION’ AND ‘EMISSION REDUCTION’?

Abstract: The contemporary landscape sees the digital economy (DE) as a pivotal driver of economic evolution. Hence, scrutinising its potential to harmonise ‘efficiency promotion’ and ‘emission reduction’ and combat the challenges of climate change in this digital epoch is imperative. This study empirically investigates the influence of DE growth by evaluating its impact on carbon emission scale and energy efficiency. The study employs econometric modelling to delve into the internal mechanisms and diverse characteristics of DE evolution that influence ‘efficiency promotion’ and ‘emission reduction’. Findings underscore a significant capacity within the DE to ameliorate energy efficiency and curtail overall carbon emissions, revealing its dual prowess in fostering ‘efficiency promotion’ and ‘emission reduction’. Robustness tests affirm these outcomes, fortifying the conclusion. Additionally, the effects of DE development on ‘efficiency promotion’ and ‘emission reduction’ are validated in these tests. The study reveals that the ‘efficiency promotion’ and ‘emission reduction’ facets of DE progression exhibit distinctive regional disparities, notably manifesting more pronounced impacts in the eastern regions.

Keywords: digital economy, energy efficiency, carbon emissions, regional heterogeneity

Introduction

The global challenge of reducing greenhouse gas emissions confronts nations worldwide. China, as the world’s foremost energy consumer and carbon emitter, contributes approximately 30 % of the total global carbon emissions and is thus under immense pressure to curtail its emissions. Acknowledging its responsibility, the Chinese government has placed paramount emphasis on environmental preservation, energy conservation and emission reduction. It actively pursues a high-quality developmental trajectory that reconciles energy conservation and emission reduction with sustained economic growth. In September 2020, President Xi Jinping articulated China’s commitment, emphasising the nation’s pledge to augment its national autonomous contribution. China aims to implement more robust policies and measures, aspiring to reach the peak of carbon dioxide emissions by 2030 and strive vigorously towards achieving carbon neutrality by 2060. This resolute stance underscores the Chinese government’s determination in the realm of energy conservation and emission reduction.

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Presently, the pivotal issue facing China revolves around effectively realising the goals of carbon peaking and carbon neutrality. Given that energy consumption is the primary source of carbon emissions, the efficacy of energy utilisation emerges as a foundational factor influencing emissions. Consequently, enhancing energy efficiency emerges as a pivotal avenue for reducing emissions [1-3]. The fundamental challenge lies in striking an equilibrium between 'efficiency promotion' and 'emission reduction'.

The digital economy (DE) is a transformative force reshaping the global economic landscape. It encompasses the production, distribution and consumption of goods and services facilitated by digital technologies [4, 5]. At its core, the DE leverages the power of information and communication technology (ICT) to streamline processes, enhance connectivity and foster innovation across industries. The roots of the DE can be traced to the advent of computing technologies in the mid-20th century. The proliferation of mainframe computers, followed by the emergence of personal computers in the 1980s, laid the groundwork for digitalisation [6-8]. The widespread adoption of the Internet in the 1990s marked a pivotal moment, catalysing the rapid expansion of digital infrastructure and connectivity. The burgeoning growth of DE presents novel solutions that require a mutually beneficial equilibrium between 'efficiency gains' and 'emission reductions'. Since the dawn of the 21st century, the global economy has traversed various stages - from the industrial to the information economy, the Internet economy, to the current era of the DE. Digitalisation has emerged as a fresh catalyst for economic expansion, fostering efficiency, speed and innovation. In 2022, the Chinese government underscored the prominence of the DE by integrating it into their work report for the fifth consecutive time, emphasising the imperative of advancing its high-quality development in this new developmental phase. Notably, China's DE scaled up to 39.2 trillion yuan in 2020, accounting for 38.6 % of the GDP, marking a growth rate of 9.7 %. Beyond its economic significance, the paramount role of DE development extends into the environmental sphere.

The study delves into the transformative impact of successive waves of technological revolutions on the economic system, particularly regarding resource utilisation and environmental sustainability. From the shift from agrarian to industrial economies to the ongoing integration of digital technology across sectors, a persistent challenge is in balancing efficiency gains with environmental consequences. This paper investigates whether the trajectory of DE development can achieve a harmonious convergence between efficiency promotion and emission reduction. The study seeks to elucidate the potential contributions of DE to sustainable development goals by empirically examining the relationship between DE development and carbon emission scale alongside energy efficiency.

Literature review

Definition of DE

To elucidate the economic and environmental ramifications of DE development, a foundational comprehension of its core tenets is imperative. The concept of DE is continually evolving and is imbued with new facets as time progresses and research depends.

ICT serves as the bedrock of DE. It delineates an economic system reliant on ICT, encompassing data and information's access, reception, conversion, storage, processing and dissemination [9, 10]. This paradigm assumes a pivotal role in China's economic metamorphosis, serving as the technological cornerstone for digital manufacturing and service industries [11-13]. The Internet stands as the conduit of the DE. Its pervasive network propels the digital transformation of human lifestyles. De et al. [14] assert that the rapid evolution of Internet technology accentuates the significance of information technology within the DE realm. The advent of the Internet dismantled temporal and spatial constraints, obliterated information asymmetry and exponentially amplified the quantity and speed of information transmission. The incorporation of Internet elements enriches the essence of DE.

Digital finance has emerged as a pivotal manifestation of the DE. This facet encapsulates a business model grounded in digital goods or services, constituting an economic modality that trades products and services in digital formats, encompassing e-commerce, digital currency and cross-border transactions. The ascendancy of digital transactions engenders novel financial business models such as mobile payments, online loans, digital insurance and cryptocurrencies. Digital finance surmounts the limitations of traditional financial services through mobile terminals and extensive big data analysis, boasting advantages of ‘low cost, high speed and broad coverage’. It assumes an indispensable role in China’s DE expansion.

Environmental effects of DE development

The advent of electronic components and integrated circuits sparked the genesis of the communication sector, prompting scholarly attention toward the environmental governance effects of ICT. Diverse studies have yielded varying conclusions regarding this nexus. Zhang and Liu [15] and Liu et al. [16] assert that ICT contributes positively to green development. Conversely, Moyer and Hughes [17] projected global carbon emissions until 2040, positing that ICT exhibits a limited downward impact on overall emissions across 50 years. Additionally, Zhou et al. [18], using the input-output method, scrutinised China’s communications industry from 2007-2012, suggesting that the ICT industry is not environmentally friendly. They highlighted the substantial implied carbon emissions from its supply chain, pinpointing the upstream sector as the primary source.

The multifaceted impact of ICT on the environment is acknowledged by Ren et al. [19], who propose an inverted U-shaped relationship between ICT and GHG emissions. They highlight the positive and negative effects of communication technologies on the environment. As communication technologies advance, the proliferation of television, computers, software and the Internet surged, causing the relationship between the Internet economy and energy intensity to reach a focal point. Scholars diverge in their assessments. Ozcan and Apergis [20] and Zhao [21] contend that increased Internet usage correlates with reduced pollutant emissions.

Conversely, Salahuddin and Alam [22], based on OECD data spanning 1991-2012, assert that while the Internet significantly impacts environmental pollution, the effect remains marginal. Examining the shift in production and lifestyle induced by the Internet, scholars probe individual activities’ environmental impact. For instance, Fuhr and Pociask [23] discovered that telecommuting facilitated a reduction of approximately 588.2 tonnes ($t = 10^6$ g = Mg) of greenhouse gas emissions in the United States over a decade.

The existing literature reveals a notable gap where comprehensive discussions concerning the ‘efficiency promotion’ and ‘emission reduction’ effects of DE development, along with their intrinsic mechanisms and heterogeneous characteristics, remain scarce. Few studies have concurrently addressed these facets within a unified analytical framework. This paper aims to integrate DE development with ‘efficiency promotion’ and ‘emission reduction’ into a cohesive analytical structure. Through theoretical analysis and empirical testing, this study endeavours to examine these dual dimensions comprehensively, bridging the gap in the current discourse.

Research hypotheses

DE development and energy efficiency

From the lens of DE development impacting energy management, the integration of digital platforms into energy management has culminated in an interconnected network of information flows. This transformation reshapes conventional energy production, transmission and consumption paradigms [24].

Leveraging information technology to construct energy infrastructure, such as the smart grid, facilitates real-time monitoring of energy demand fluctuations, which aids in swiftly balancing energy supply and demand, thereby enhancing transmission efficiency. Moreover, the influence of ICT, digital platforms and Internet concepts pervades enterprise operations comprehensively - from design and manufacturing to management and sales. This influence empowers enterprises to continuously upgrade resource utilisation and energy conservation technologies, revolutionising various facets of production and operations.

DE’s impact on technological innovation stems from the amalgamation of digital technology with traditional production methods. This convergence steers industrial production towards automation, intelligence and energy efficiency. Heightened efficiency in information transfer and interchange amplifies knowledge spillover and diffusion among enterprises, augmenting product value.

Furthermore, DE’s influence is more pronounced in sectors with high carbon footprints, like transportation. The transportation industry, being notably carbon-intensive, crucially contributes to lifestyle decarbonisation. In the era of globalisation, information technology has become indispensable for transportation, warehouse and logistics operations. Intelligent logistics networks and transportation systems enable optimised route planning, mode switching and inventory management, culminating in improved transport efficiency and energy conservation.

This perspective on the impact of DE development on industrial characteristics underscores the distinctive traits of the DE: economies of scale, economies of scope and the long-tail effect. The expansion of information resources and accelerated flow rates amplify the marginal return of information, enticing substantial capital investment into the digital industry. Simultaneously, this phenomenon stimulates the consumer market from the supply and demand perspectives. Manufacturers leverage intelligent technology to observe and respond keenly to market dynamics, while consumers express diverse needs more conveniently. The integration of the financial market via the Internet has also revolutionised financial operations, reducing transaction costs and enhancing transaction efficiency. Consequently, DE development effectively combats information asymmetry prevalent in traditional production and consumption, thereby mitigating resource mismatch and fostering optimal allocation and utilisation efficiency, including in traditional energy production.

Based on these observations, this paper posits the following:

Hypothesis 1: The development of the DE contributes to energy efficiency, exhibiting an ‘efficiency promotion’ function.

DE development and carbon emissions

DE harbours immense potential for environmental rejuvenation, particularly in the context of carbon transfer pathways., the digital industry demonstrates an environmentally friendly disposition when examined from the prism of carbon sources. It gradually phases out highly polluting and antiquated production entities by squeezing traditional industries, rendering old production methods cleaner and more efficient through continuous integration with traditional sectors.

Moreover, regarding carbon processing, the application of sensors, wireless communication, big data and Internet technologies in carbon emission monitoring and management facilitates real-time data analysis, which enables predictive modelling of carbon emission trends and facilitates online supervision and processing. Additionally, the DE propels the development and application of carbon dioxide treatment technologies, such as carbon capture, utilisation and sequestration, along with network system solutions, offering substantial market potential and carbon reduction capabilities.

Delving deeper, the DE exhibits varying degrees of permeability across primary, secondary and tertiary industries, reshaping the trajectory and pace of industrial evolution.

Industrial Structure Adjustment: Information technology predominantly bolsters the development of the service consumption field, with the tertiary industry experiencing higher penetration levels compared to other sectors. This development not only facilitates an economic shift from heavy industry to a knowledge and service-centric economy but also fosters productive service industries characterised by virtualisation and networking. The typically less energy-intensive nature of the service industry, coupled with the burgeoning scale of the tertiary industry, leads to a partial decoupling of economic growth from energy consumption. This phenomenon slows down overall carbon emissions or even curtails their growth.

Industrial Structure Upgrading: The increasing entwining of data elements with traditional production factors deepens the integration of production and service realms across geographical boundaries and temporal constraints, prompting industries to evolve toward intelligence, thereby curbing carbon emissions. Notably, energy efficiency, intrinsic to the ‘efficiency promotion’ function of DE development, serves as a pivotal driver in reducing carbon emissions.

Hence, this paper posits the following:

Hypothesis 2: The development of the DE contributes to carbon reduction, exhibiting an ‘emissions reduction’ function.

Methods

Model design

This paper constructs the following benchmark regression model to examine the ‘efficiency promotion’ and ‘emission reduction’ effects of DE development:

$$EE_{it} = \beta_0 + \beta_1 digital_{it} + \beta_2 X_{it} + u_i + v_t + \varepsilon_{it} \quad (1)$$

$$EC_{it} = \beta_0 + \beta_1 digital_{it} + \beta_2 X_{it} + u_i + v_t + \varepsilon_{it} \quad (2)$$

where i denotes the name of the province, and t represents the year, respectively, and the explanatory variable EE_{it} is energy efficiency, EC_{it} is the total carbon emissions, $digital_{it}$ denotes the core explanatory variable DE development, and$\mathrm{X_{it}}$ denotes the control variable. β_0 represents constant terms, β_1 and β_2 denote the coefficients to be estimated; u_i and v_t denote area- and time-fixed effects, respectively, and ε_{it} denotes the random perturbation term.

Variables and data

In this paper, panel data from 30 provinces in China (except Hong Kong, Macao, Taiwan and Tibet) from 2011 to 2020 are selected as research samples. The specific descriptions of the relevant indicators are as follows:

(1) Carbon emissions. The scale of carbon emissions is carbon dioxide emissions. In calculating carbon emissions, this paper adopts the carbon emission coefficients and calculations published by the United Nations Intergovernmental Panel on Climate Change:

$$EC = \sum_{i=1}^{8} E_i \cdot \mathrm{NCV_i} \cdot CEF_i \cdot COF_i \cdot \frac{44}{12} \tag{3}$$

where EC is the calculated CO_2, i = 1 ,…, 8 denote the eight energy sources, namely coal, coke, crude oil, gasoline, kerosene, diesel, fuel oil and natural gas, E_i is the consumption of the i-th energy, NCV_i is the average low heat value of the i-th energy, CEF_i is the carbon emission coefficient of the i-th energy and COF_i is the oxidation rate of the i-th energy, which is usually 1.

(2) Energy efficiency. This paper uses the inverse of the ratio of total energy consumption to GDP to portray regional energy efficiency.

Table 1

The evaluation index system of DE development index

Target	Standard		Index	Unit
DE	Information development	Information infrastructure	Optical cable density	km/km^2
			Mobile phone base station density	10,000/km^2
		Communication service level	Mobile phone penetration rate	Department/100 people
			Proportion of informatisation employees	%
		Information application	Total telecom service	10,000,000 times
	Internet development	Internet penetration	Proportion of Internet users	%
			Proportion of Internet broadband access users	%
		Internet infrastructure	Internet broadband access port density	10,000/km^2
			Number of domain names	10,000 times
		Internet application	Software business income	10,000 times
	Digital finance		Digital Inclusive Finance Index	-
			Coverage of digital finance	-
			Depth of use of digital finance	-
			Digitalisation of inclusive finance	-

(3) DE development. The development of DE is extremely complex and measuring it with a single indicator is not objective and comprehensive enough. Hence, many scholars measure the level of DE development by establishing an indicator system. This study constructs a DE development index system from three dimensions of ICT, Internet and digital finance, as shown in Table 1, based on the theoretical framework of DE in the previous section. The factor analysis method is used to calculate the DE development index of each province.
(4) Control variables. The control variables selected in this paper include population size (*POP*), urbanisation (*UR*), opening to the outside world *(OPEN*), government intervention (*Gov*) and infrastructure (*Base*). Among these factors, population size is expressed by the total population at the end of the year, urbanisation is expressed by the proportion of urban population to the total population, government intervention is expressed by the ratio of government fiscal expenditure to GDP and infrastructure is expressed by the number of highway miles per capita.

Empirical analysis

Benchmark regression

The findings from the baseline regression analysis, as presented in Table 2, underscore significant insights into the impact of DE development on energy efficiency and carbon emissions. Columns (1) and (3), without control variables, and columns (2) and (4), with control variables, depict nuanced effects.

DE Development and Energy Efficiency: Columns (1) and (2) demonstrate a notably positive impact of DE development on energy efficiency. For every 1 unit increase in DE development, energy efficiency escalates by approximately 0.1227 to 0.1504. This finding robustly supports the proposition that DE development functions as an efficiency promoter.

DE Development and Carbon Emissions: Columns (3) and (4) reveal a significantly negative impact of DE development on carbon emissions. In essence, a tangible reduction in carbon emissions can be observed as DE development intensifies, corroborating the notion that DE development effectively drives emission reduction.

The synthesis of these analyses leads to a compelling conclusion: DE development adeptly balances the dual functions of 'efficiency promotion' and 'emission reduction'. Hence, Hypotheses 1 and 2 find substantiation within these empirical findings.

Table 2

Benchmark regression analysis

Items	***EE***		***EC***	
	Model (1)	**Model (2)**	**Model (3)**	**Model (4)**
digital	0.1504**	0.1227**	–0.059*	–0.077***
	(4.90)	(3.96)	(–1.836)	(–3.241)
CV	NO	YES	NO	YES
Time-fixed effect	YES	YES	YES	YES
Province-fixed effect	YES	YES	YES	YES
Obs	300	300	300	300
R^2	0.6152	0.7722	0.7381	0.8916

Note: () is *t* statistic; ***, ** and * represent the significance levels of 1 %, 5 % and 10 % respectively; R^2 - the correlation coefficient.

Robustness tests

This study employs a methodology centred on substituting key explanatory variable indicators to ensure robustness in the estimation outcomes. This paper gauges the development of DE by adopting the output value of the digital industry as a proxy variable, considering the paramount role of data in DE development. According to this perspective, the infrastructure influencing data transmission and processing, particularly the information network and data carrier facilities, significantly influences DE evolution.

Consequently, this study selects the output values from the ‘information transmission, software, and information technology service industry’ and the ‘computer, communication, and other electronic equipment manufacturing industry’ as the metrics to assess the digital industry’s output value. Additionally, the output value of the ‘culture, sports, and entertainment industry’ is taken as a proxy variable representing DE development. This sector is incorporated into the digital industry output value index considering its role as a digitalised carrier facilitating the accommodation and dissemination of data elements. This amalgamation of the three industry output values forms a proxy variable indicative of DE development.

Findings delineated in columns (1) and (2) of Table 3 reveal sustained significant effects of ‘efficiency promotion’ and ‘emission reduction’ in DE development even after the replacement of core explanatory variables.

Moreover, the instrumental variable technique was employed to bolster the model’s robustness and mitigate errors and endogeneity stemming from omitted variables. A one-period lag of the DE development Index was utilised as the instrumental variable. The findings, elucidated in columns (3) and (4) of Table 3, epitomise the results of the 2SLS regression analysis.

The 2SLS regression results underscore the significant augmentation of energy efficiency and the effective mitigation of carbon emissions attributable to digital economy development. Significantly, the coefficient estimations align consistently with the fixed effect results in the baseline model, indicating proficient control over deviations induced by unobserved factors in the baseline model.

Table 3

Robustness test results

Items	**Replace the core explanatory variables**		**Control endogeneity**	
	Model (1)	**Model (2)**	**Model (3)**	**Model (4)**
	EE	***EC***	***EE***	***EC***
digital	0.1627***	–0.0574***	0.7943***	–0.1255***
	(3.68)	(–5.21)	(5.25)	(–2.81)
CV	YES	YES	YES	YES
Time-fixed effect	YES	YES	YES	YES
Province-fixed effect	YES	YES	YES	YES
Obs	300	300	300	300
R^2	0.7556	0.8144	0.6538	0.6861

Heterogeneity analysis

Table 4 presents a comprehensive analysis of the nuanced regional dynamics within the realm of DE development. It meticulously outlines the discernible disparities between the eastern region and the central and western regions, elucidating the multifaceted influences of economic structures, demographic compositions, resource endowments, and developmental trajectories.

The intricate interplay of geographical factors, such as varying terrain relief levels, adds another layer of complexity to the establishment of digital infrastructure and associated equipment. This influence further accentuates the divergent trajectories of DE development across heterogeneous terrain areas, painting a vivid picture of the spatial heterogeneity inherent in digital economic transformations. Stratifying regions into eastern, central and western categories allows for a nuanced examination of their respective developmental trajectories and facilitates a granular analysis that unveils the underlying drivers of regional heterogeneity in DE development.

Table 4

Heterogeneity analysis

Items	*EE*		*EC*	
	Model (1)	**Model (2)**	**Model (3)**	**Model (4)**
	East	**Middle and West**	**East**	**Middle and West**
digital	0.1827^{***}	0.1054^{**}	-0.0703^{***}	-0.0451^{***}
	(5.66)	(1.99)	(–3.06)	(–2.93)
CV	YES	YES	YES	YES
Time-fixed effect	YES	YES	YES	YES
Province-fixed effect	YES	YES	YES	YES
Obs	90	210	90	210
R^2	0.8277	0.7308	0.7912	0.7872

The findings of dissecting the dimensions of energy efficiency reveal a compelling narrative of ‘efficiency promotion’ across both regions. However, a closer examination exposes the eastern region’s remarkable prowess in this regard, outpacing its counterparts in the central and western regions. This phenomenon underscores the intricate interplay of various factors, including technological adoption, regulatory frameworks, and investment patterns, in shaping regional disparities in energy efficiency outcomes.

Similarly, the analysis of carbon emissions reduction unveils a striking divergence between the eastern and the central and western regions. While DE development exerts a positive influence on carbon emissions reduction across all regions, the magnitude of impact varies significantly. The eastern region once again emerges as a frontrunner, significantly surpassing its counterparts in mitigating carbon emissions through digital economic transformations.

Conclusion

The study’s findings underscore the significant impact of DE on energy efficiency enhancement and emission reduction. However, future research should extend the temporal scope of analysis beyond 2020 to comprehensively understand the dynamics of DE’s influence. Longitudinal studies would allow for tracking evolving trends and assessing the sustained effectiveness of DE initiatives in promoting efficiency and curbing emissions over time. Moreover, sector-specific investigations are warranted to elucidate how DE development affects energy efficiency and emissions across various industries. Researchers can identify specific areas where DE interventions can yield the greatest benefits and inform targeted policy interventions and resource allocation strategies by examining sectoral nuances.

Technological innovation stands out as a crucial factor in amplifying the impact of DE on efficiency enhancement and emission reduction. Future research should explore the role of emerging technologies, such as artificial intelligence and Internet of Things applications, in enhancing DE efficacy and scalability. Understanding the adoption dynamics of these technologies can provide valuable insights for optimising DE deployment strategies. Policy evaluation and design represent another critical research avenue. Assessing the effectiveness of existing policies aimed at promoting DE development and designing innovative policy instruments, such as regulatory frameworks and incentive programs, can further incentivise DE adoption and maximise its contributions to efficiency enhancement and emission reduction. The spatial analysis offers an opportunity to examine regional variations in DE deployment and its implications for efficiency and emissions. Investigating urban-rural disparities in DE accessibility and adoption rates can inform targeted interventions for equitable development and ensure that the benefits of DE are distributed across diverse socio-economic contexts.

This paper proposes strategic industry shifts towards intelligence and energy conservation based on its conclusions. It suggests moving away from the antiquated heavy industry development models to prioritise fostering a productive service industry, particularly the digital sector. One proposed strategy involves establishing industrial Internet parks and leveraging industrial clustering to disseminate knowledge and technology. Advancements in digital production technologies such as virtual manufacturing, industrial robotics, intelligent sensors and mechanical equipment are recommended to support this transition.

Additionally, recommendations include strengthening ICT infrastructure in both urban and rural areas to promote the creation of ‘smart cities’ and digital villages while mitigating over-reliance on traditional resources. Accelerating the development of digital platforms and network systems to monitor energy demand, enable proactive power distribution planning and implement automatic alerts for hazardous situations is advocated. Furthermore, deploying digital technologies for energy exploration and transportation, utilising cloud computing and the Internet of Things for visual management systems is proposed to enhance efficiency and sustainability.

Acknowledging technological disparities in high-terrain areas within the DE landscape, the paper emphasises incentivising technologically advanced regions to lead development efforts. Overcoming technological barriers in underdeveloped areas through increased capital investment and addressing construction challenges is highlighted. The deployment of digital facilities in rugged terrains, including installation, debugging and operational considerations, is identified as crucial for effectively leveraging the advantages of DE in high-terrain regions, aiming for efficiency gains and emission reductions.

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