

Nian MA¹ and Ying DENG^{1*}

SYNERGISTIC GOVERNANCE OF DIGITAL ECONOMY DEVELOPMENT AND CARBON REDUCTION: EVIDENCE FROM CHINESE CITIES

Abstract: As a fundamental driving factor for high-quality advancement, elucidation remains requisite regarding the potential of the digital economy (DE) in achieving conjoined governance aimed at pollution reduction and carbon reduction (PCR). This study conducts a comprehensive analysis of the nexus between digital economic development (DED) and carbon mitigation. Empirical analyses are conducted utilising panel data encompassing Chinese municipalities from 2011 to 2020, enabling a quantitative evaluation of the influence exerted by DED on the concerted governance of carbon reduction and haze mitigation. The results emphasise that: DED cultivates conducive circumstances for curtailing carbon emissions and addressing haze pollution, with subsequent robust testing reinforcing the enduring significance of DED's impact on PCR. Heterogeneity analysis reveals the pronounced effect of DED on PCR, particularly discernible in provincial capitals, eastern municipalities, as well as first and second-tier urban centers, alongside metropolises of significant magnitude. The reciprocal impact of DED on PCR predominantly stems from industrialisation synergies, primarily attributed to the optimisation and advancement of industrial structure, concomitant with enhancements in production efficiency.

Keywords: digital economy, pollution and carbon reduction, collaborative governance, spatial spillovers

Introduction

China's ecological civilisation establishment stands at a critical phase underscored by president Xi Jinping's emphasis on prioritising carbon reduction as the pivotal strategic trajectory. This underscores the pursuit of fostering a confluence between pollution reduction and carbon reduction (PCR), propelling the overarching green transition of economic and social development, thereby effectuating a qualitative leap in the ecological environment's quality. Aligned with the broad requisites of PCR, each region distinctly advocates for the synergistic advancement encompassing carbon reduction, pollution abatement, and green growth. This action strategy aims for synergy in various dimensions including field, task, policy, and regulatory realms, collectively contributing to environmental governance. Nevertheless, the tangible outcomes of this synergistic management of PCR present a sobering picture, subject to the multifaceted influence of diverse factors such as energy structure and efficiency [1-3]. Achieving the goals of synergistic management hinges not on a single subsystem but demands intertwined efforts across multiple domains like economic, technological, and energy systems. Ultimately, the

¹ School of Economics and Management, Wuhan University of Engineering Science, Wuhan, 430200, China, ORCID: NM 0009-0004-4278-7419, YD 0009-0008-5161-6581

* Corresponding author: 15871783676@163.com

successful synergistic governance of PCR urgently necessitates innovative environmental policy tools and the overhaul of the environmental governance framework.

Simultaneously, amid the rapid evolution of the digital economy (DE), regions lay forth new imperatives to enhance DE prowess, particularly focusing on invigorating empowerment and efficiency. Efforts are directed towards leveraging DED as a cornerstone to foster the synergistic advancement of PCR. The foundation of DE evolution lies fundamentally in digital technology's application as a nucleus, bolstered by digital service platforms, playing a pivotal role in transforming production methods, lifestyles, and governance modalities. Theoretically, Digital Economic Development (DED) holds the potential to enhance environmental governance decision-making efficacy by assimilating, integrating, and analysing environmental information elements. DED also contributes to synergistic pollution and carbon governance through preventive measures at the source, process control, and end-stage management. Ergo, rooted in DED's fundamental essence, this paper centrally focuses on the coordinated governance objective of PCR. It integrates DED and PCR into a cohesive analytical framework, delving into the driving mechanisms and pathways through which DED facilitates the coordinated governance of PCR.

Theoretically, the evolution of the DE holds the promise of refining resource allocation by leveraging information technology applications and data platform services, thereby fostering multidimensional innovations across production methodologies, management paradigms, and product services [4-7]. Concretely, DE advancement stands to enhance the configuration of production factors by leveraging sharing platforms, engendering novel low-carbon economic models, broadening the scope of clean industry applications, consequently curbing emissions of carbon dioxide and air pollutants. Simultaneously, DED facilitates a deeper integration of digital technology into environmental stewardship, augmenting the calibre of environmental oversight and fortifying the external checks on clean production. Moreover, DE progression enables adaptable production by finely calibrating consumer demand preferences and scale, thereby enhancing production efficiency and mitigating capacity wastage, culminating in heightened resource utilisation efficiency and the realisation of clean production paradigms. This study posits that the influence of DED on the coordinated management of PCR primarily stems from the optimisation and advancement of industrial structure alongside the augmentation of production efficiency.

Regarding the optimisation of the industrial structure, the evolution of the DE manifests several key impacts. Firstly, DED dismantles barriers obstructing the flow of production factors, expediting the convergence of talents, scientific prowess, and other innovative factors. This deepens the amalgamation and assimilation of pioneering production elements with conventional factors like energy and labour, effectuating industrial enhancement through structural optimisation [8-10]. Secondly, the augmented influx of innovative elements such as data catalyses transformations in production, management, and operational paradigms, ultimately propelling the metamorphosis and advancement of industrial composition [11-13]. Thirdly, DE advancement births novel economic configurations and industrial models like smart finance and smart tourism. The emergence of these sectors triggers the "repatriation" of production factors from traditional industries, fostering further refinement in the industrial framework. Building upon these facets, optimising the industrial structure not only curtails energy consumption by displacing antiquated, energy-intensive, and polluting industries while renovating

obsolete production capacities, but also fosters the efficient allocation of factors, thereby actualising synergistic PCR management.

At the frontier of productivity enhancement, the progression of the DE initiates several pivotal transformations. Firstly, DE's advancement facilitates the augmentation of digital infrastructure. The establishment of information cloud platforms and databases expedites the seamless integration and swift circulation of data elements, fully leveraging the reservoir-like capacity of data [14, 15]. This aggregation of data factors not only fosters knowledge and technological spillovers, augmenting innovation prowess, but also bolsters the delineation of tasks, curbing unnecessary resource wastage and energy losses across various production nodes, thereby bolstering production efficiency. Secondly, DED alleviates information asymmetry, stimulating the circulation and configuration of knowledge, technology, and related factors, thereby furnishing substantial support for green technology innovation. Furthermore, DE's development functions as a magnet for talent, attracting innovative minds and fostering a conducive research milieu, consequently elevating the efficiency of green technology research and development.

Green technology innovation constitutes a pivotal pillar in enhancing energy efficiency and environmental quality [16]. On one front, it facilitates the development and utilisation of clean energy, diminishing reliance on traditional fossil fuels. Simultaneously, it optimises production processes and workflows, curbing energy wastage during production and ultimately fostering synergistic PCR management.

The study aims to analyse how the DE influences coordinated efforts to PCR. The innovations of this paper are multifaceted. Firstly, it delves into the impact of DED within the environmental sphere from the novel vantage point of PCR's synergistic governance, enriching DE-related literature. Secondly, it scrutinises the heterogeneous effects of DED on PCR's synergistic governance across diverse dimensions, unveiling divergent PCR outcomes in various scenarios. Lastly, the paper dissects the synergistic governance mechanism of PCR through DED, examining industrial structure optimisation, upgrading, and production efficiency enhancement, thereby enhancing the theoretical framework of DED.

Literature review

The literature relevant to this paper falls into two primary categories:

The first category involves assessing the synergistic effect of emissions reduction within PCR and analysing its determinants. Presently, a standardised approach to evaluating the joint emissions reduction effect of greenhouse gases and air pollutants is lacking. Research methodologies in this domain can be broadly classified into two types: The synergistic emission reduction coefficient method quantifies historical joint emissions reduction by establishing coefficients that capture the reduction of greenhouse gases and air pollutants. This category of research typically employs regression analysis to compute synergistic coefficients between different types of pollutant emissions and assesses their significance. The synergistic emission reduction simulation method involves simulating equivalent reductions based on projected policy objectives or engineering parameters. For instance, Zhou et al. [17] conducted simulations under varied scenarios by setting different emission reduction goals and policy intensities, comparing the synergistic effects under different parameters to identify optimal pathways for joint emissions reduction.

To delve deeper into the determinants influencing the joint reduction of carbon emissions and air pollutants, related studies have examined factors across national, regional, and industrial levels. Economic scale, technological progress, industrial structure, and environmental regulations are highlighted as crucial factors that potentially impact the joint reduction of greenhouse gases and air pollutants. These studies aim to elucidate how these elements influence the synergistic emission reduction across various scales and settings.

The second category revolves around interpreting the essence and analysing the environmental implications stemming from the advancement of the DE. Presently, a unified conceptualisation of DE remains elusive, primarily comprising two facets: industrial digitisation and digital industrialisation. Fundamentally, DE's evolution involves an intensified application of digital technology in industrial functions, aiming to enhance service quality, operational efficiency, and competitiveness by reforming traditional economic development models. DED extends beyond a narrow economic realm, permeating various dimensions such as digital governance, production, and daily life.

At the foundational economic level, DED underscores the utilisation of data as a novel production factor, fostering innovation in products, services, and business models via digital service platforms and production technologies [18]. At the societal service level, DED enhances service organisation structures, optimising processes tailored to the individual needs of urban dwellers [19], thereby elevating the quality of social services through digital applications [20]. At the infrastructure tier, DED propels the construction of digital infrastructure, like urban digital service platforms and information databases, fostering an environment conducive to digital applications in economic and social service spheres. Effectively, DED enhances economic operation efficiency, augments the efficiency of social service modes and resource management, thereby curbing social service costs and unnecessary resource wastage, ultimately contributing to improved city performance in environmental governance.

However, regarding DED's synergistic governance effect on PCR - the focus of this paper - existing literature lacks comprehensive discussions. However, prior discussions on DED's impact on environmental quality provide valuable insights. Leveraging this, the paper constructs an econometric model to empirically test the PCR effects of DED, seeking to fill this research gap and provide empirical evidence for the interplay between DED and PCR synergistic governance.

Research design

Econometric modelling

Stata statistical analysis software was used in the study, to identify the synergistic governance effect of PCR in the DED, this paper constructs the following model:

$$CO_{2it} = \alpha_0 + \alpha_1 DI_{it} + \alpha_2 X_{it} + \mu_i + \nu_t + \varepsilon_{it} \quad (1)$$

$$PM2.5_{it} = \alpha_0 + \alpha_1 DI_{it} + \alpha_2 X_{it} + \mu_i + \nu_t + \varepsilon_{it} \quad (2)$$

where i denotes city, t - year, and CO_{2it} - the per capita carbon emissions of the explanatory variable city, and $PM2.5_{it}$ - the explanatory variable city $PM2.5$ concentration, and DI_{it} - the core explanatory variable DED; α_0 - the constant term α_1 and α_2 - the coefficients to be estimated. This paper focuses on the estimated coefficients of α_1 . If α_1 is significantly negative, it indicates that DED can promote carbon emission reduction and

haze management at the same time; X_{it} denotes the control variables; μ_i - city fixed effects, the ν_t - year fixed effects, and ε_{it} - random perturbation term.

Data sources

In this paper, the panel data of 273 cities at prefecture level and above in China from 2011 to 2020 are selected as the research sample. The selection of these cities in China was guided by several factors aimed at ensuring geographic diversity and representativeness of the overall economic landscape. Specifically, the provinces were chosen based on the following criteria:

Geographic distribution: The selected provinces encompass a broad geographical spread, covering diverse regions across China, including coastal areas, inland provinces, and western regions. This geographic diversity allows for the examination of regional disparities and variations in digitalisation levels and economic performance.

Economic significance: The provinces chosen represent a mix of economically advanced regions, such as Guangdong, Jiangsu, and Zhejiang, which are hubs of manufacturing and innovation, as well as less-developed provinces in central and western China. This variation in economic development stages facilitates the analysis of how digitalisation influences economic growth and development across different contexts.

Population and economic activity: The selected provinces account for a significant proportion of China's population and economic activity, making them key drivers of national growth and development. By focusing on provinces with substantial economic contributions, the research aims to capture trends and dynamics that are indicative of broader national patterns.

The relevant variables are specified as follows:

- (1) Measurement of urban carbon emissions in existing studies primarily relies on various methods such as the carbon emission coefficient method, life cycle assessment, and input-output analysis [21]. The carbon emission coefficient method calculates emissions based on conversion factors for different energy sources. Life cycle assessment tracks emissions across a product's entire life cycle, while input-output analysis computes terminal emissions using elemental input-output scales and efficiencies. However, a standardised and scientifically rigorous carbon emission accounting method is yet to be established, leading to discrepancies in data due to differing data acquisition methods and statistical approaches. Some scholars have suggested using satellite remote sensing data for carbon emission estimation, employing a top-down approach by inversely simulating carbon dioxide emissions from nighttime light data [22, 23]. This approach focuses on three energy consumption types - natural gas, liquefied petroleum gas, and electricity - while omitting transportation-related emissions due to data scarcity and their lower contribution to overall carbon emissions. Although the proportion of coal-fired power generation varies across cities, assuming a consistent proportion of coal-fired power generation simplifies the analysis due to marginal differences.
- (2) PM2.5 concentration as an air pollutant is derived from a combination of Tsinghua University's PHD database containing PM2.5 concentration data from 2000 to 2016 and the National Urban Air Quality Real-time Distribution Platform providing annual averages of urban PM2.5 concentration from 2013 to 2020.
- (3) DED. Existing studies predominantly utilise the Internet development level to depict the DE but often overlook its essence as a transactional mode reliant on network

platforms. This oversight leads to inadequate representation of economic attributes and financial characteristics in DE estimation. To address this, this paper constructs an assessment system to gauge DE development at the city level in China, integrating Internet and digital financial development. Specific sub-indicators related to Internet development encompass the output of the Internet industry measured by per capita telecommunication service volume, employment in the Internet industry indicated by the proportion of computer workers in the workforce, Internet penetration gauged by the number of Internet users, and mobile communication coverage indicated by mobile phone ownership per 100 individuals. This index includes sub-indicators like coverage breadth, usage depth, and digitisation levels. The DE level measured in this paper is derived through principal component analysis and dimensionality reduction techniques.

- (4) Industrial structure transformation and upgrade denote the dynamic shift from lower to higher forms, particularly emphasising the transition towards a more service-oriented economic structure. To measure this shift in the overall economic structure, the ratio between the added value proportion of the tertiary industry to GDP and the added value proportion of the secondary industry to GDP is employed. This ratio serves as a metric to assess the optimisation and upgrade of the industrial structure, emphasising the increasing dominance of the tertiary sector over the secondary sector in the economy's value generation.
- (5) Productivity measurement in this study employs the Efficiency Based Model - Data Envelopment Analysis model to assess total factor productivity at the city level. Inputs considered comprise capital stock estimated using the perpetual inventory method, labour represented by the number of employed individuals at year-end, and total energy consumption derived from aggregating primary energy consumption. Meanwhile, the city's GDP, levelled and set at 2011 as the base period, is selected as the desired output.
- (6) Control variables selected in this paper to account for potential influences on synergistic emission reduction include:
 - Population size (*POP*): Represented as the logarithm of the year-end total population.
 - Fiscal expenditures (*FA*): Quantified as the ratio of fiscal expenditures to GDP.
 - Environmental regulation (*ER*): Measured as the ratio of environmental governance expenditures to fiscal expenditures.
 - Foreign direct investment (*FDI*): Indicated by the ratio of actual utilised foreign investments to GDP.
 - Economic development: Represented by per capita gross regional product (*PGDP*) and its squared term ($PGDP^2$).
 - Urbanisation rate (*UR*): Measured as the ratio of urban population to total population.

Empirical analysis

Benchmark regression analysis

Table 1 presents the influence of DED on urban per capita carbon emissions and PM_{2.5} concentration. Columns (1) and (3) display results without control variables, while columns (2) and (4) incorporate these controls. Analysis of columns (1) and (2) reveals a consistently significant negative impact of DED on urban per capita carbon emissions,

indicating its role in reducing emissions. Similarly, examination of columns (3) and (4) indicates a significantly negative impact of DED on PM2.5 concentration, suggesting its dual effect in reducing carbon emissions and managing haze pollution. Thus, DED demonstrates a synergistic management effect on PCR.

Table 1

The benchmark regression analysis

Variables	CO ₂		PM2.5	
	Model (1)	Model (2)	Model (3)	Model (4)
<i>DI</i>	−0.0349 ^{***} (−2.09)	−0.0278 ^{***} (−2.14)	−0.0308 ^{***} (−2.47)	−0.0186 [*] (−1.90)
CV	NO	YES	NO	YES
City-fixed effect	YES	YES	YES	YES
Time-fixed effect	YES	YES	YES	YES
Obs	2730	2730	2730	2730
<i>R</i> ²	0.3267	0.3478	0.4019	0.3221

Note: ***, ** and * respectively indicate passing the test at the significance level of 1 %, 5 % and 10 %

Robustness analysis

The control variables that the development of digital economy affects the collaborative governance of pollution reduction and carbon reduction may be omitted, thus inducing potential endogeneity problems. To alleviate the endogeneity problem, this paper uses the number of books in public libraries in the city (*BOOK*) as an instrumental variable. To fortify the reliability of the estimation outcomes, this study conducts several robustness analyses:

Excluding Contemporaneous Policy Interference: urban PCR could be influenced by contemporaneous environmental policies. Thus, this paper excludes cities subjected to pilot low-carbon city initiatives and comprehensive energy-saving fiscal policies to refine the urban sample.

Adjusting Urban Carbon Emission Estimation Method: utilising inverse simulation of carbon dioxide emissions derived from nighttime lighting satellite data enhances accuracy. Across different robustness tests outlined in Table 2, DED consistently demonstrates positive synergistic governance effects on PCR. These findings affirm the reliability of earlier conclusions.

Table 2

The robustness test

Variables	Eliminate policy interference		Replace the interpreted variable		Stage one	Stage two	
	Model (1)	Model (2)	Model (3)	Model (4)	Model (5)	Model (6)	Model (7)
<i>DI</i>	−0.0418 ^{**} (−2.36)	−0.0322 ^{**} (−2.05)	−0.0300 ^{**} (−2.48)	−0.0319 ^{**} (−2.17)		−0.0264 ^{**} (−2.11)	−0.0306 ^{**} (−2.25)
<i>BOOK</i>					1.2185 ^{***} (2.86)		
CV	YES	YES	YES	YES	YES	YES	YES
City-fixed effect	YES	YES	YES	YES	YES	YES	YES
Time-fixed effect	YES	YES	YES	YES	YES	YES	YES
Obs	2216	2216	2730	2730	2730	2730	2730
<i>R</i> ²	0.3177	0.4017	0.2983	0.3862			
F-value						14.29	51.06

Moreover, potential endogeneity concerns stemming from omitted control variables in the previous analysis of DED's impact on PCR are addressed. This variable serves dual purposes: reflecting local human capital and innovation linked to urban DE, while maintaining exogeneity regarding direct impact on carbon emissions and PM2.5 concentration. Employing the two-stage instrumental variable method (2SLS-IV) for analysis, the first stage indicates a significantly positive relationship between library collections and DED, aligning with theoretical expectations. Subsequent estimation in the second stage, after mitigating potential endogeneity issues, continues to demonstrate a significantly negative impact of DED on per capita carbon emissions and PM2.5 concentration.

Heterogeneity analysis

DED relies on robust digital infrastructure, demanding substantial resources in manpower, materials, and finance. Cities with high DED often exhibit robust development capabilities, and city size serves as a reflection of a city's foundational development. Compared to smaller cities, larger cities hold greater promise for DE advancement. This study categorises cities as large-scale (*Size_B*) and small-scale (*Size_S*) based on median year-end residential population. The interaction between city size and DED is examined in Table 3, columns (1) and (4), revealing a more pronounced synergistic governance effect of PCR through DED in larger cities. This is attributed to the more comprehensive digital infrastructure in larger cities, fostering an environment conducive to innovation and industrial growth, consequently fostering synergistic PCR governance.

Table 3

The heterogeneity analysis

Variables	CO ₂			PM2.5		
	Model (1)	Model (2)	Model (3)	Model (4)	Model (5)	Model (6)
<i>DI</i> × <i>Size_B</i>	−0.0384*** (−3.36)			−0.0356** (−2.29)		
<i>DI</i> × <i>Size_S</i>	−0.0247** (−2.09)			−0.0260** (−2.11)		
<i>DI</i> × <i>Zy_Z</i>		−0.0189* (−1.70)			−0.0205 (−1.48)	
<i>DI</i> × <i>Zy_F</i>		−0.0335*** (−2.75)			−0.0284** (−2.36)	
<i>DI</i> × <i>GDP_B</i>			−0.0297*** (−3.00)			−0.0284** (−2.47)
<i>DI</i> × <i>GDP_A</i>			−0.0221** (−2.18)			−0.0194** (−2.06)
CV	YES	YES	YES	YES	YES	YES
City-fixed effect	YES	YES	YES	YES	YES	YES
Time-fixed effect	YES	YES	YES	YES	YES	YES
Obs	2730	2730	2730	2730	2730	2730
<i>R</i> ²	0.2784	0.4155	0.3012	0.2738	0.5082	0.4782

Resource endowment significantly influences resource utilisation efficiency and a city's industrial structure. High reliance on resource-dependent industries may lead to the "resource curse", impacting urban carbon emissions and haze pollution. This study investigates the heterogeneous effects of urban DED on pollution reduction and carbon synergy through the resource endowment lens, categorising cities as resource-based (*Zy_Z*)

and non-resource-based (Zy_F) using the "National Resource-Based Cities Sustainable Development Plan (2013-2020)". Results in Table 3, columns (2) and (5), reveal that DED in non-resource cities exhibits positive and significant synergistic governance effects on PCR. Conversely, the impact of DED in resource cities on per capita carbon emissions and PM2.5 concentration appears relatively weak. This disparity arises from the higher prevalence of "three-high" industries in resource cities, impeding industrial structure transformation and hindering the adoption of clean production technology, thereby hampering both DE development and emission reduction efforts.

Regarding the economic development dimension, cities are segmented into leading (GDP_B) and lagging (GDP_A) categories based on median disposable income per capita. Results presented in columns (3) and (6) of Table 3 demonstrate that DE development contributes to pollution reduction and carbon synergy across cities with varying economic development levels. However, the impact is more pronounced in economically advanced cities. This aligns with the expectation that economically developed cities exhibit heightened environmental aspirations, and DED serves to reinforce environmental regulations, consequently expediting PCR efforts.

Mechanism analysis

The empirical results validate the theoretical expectation regarding the intrinsic mechanism of emission reduction through DED. Specifically, DED contributes to pollution reduction and carbon synergy by optimising industrial structure and enhancing production efficiency. Findings in Table 4, columns (1) and (2), demonstrate a positive and significant impact of DED on optimising and upgrading industrial structure, along with improving production efficiency. Subsequent results in columns (3) and (4) indicate that both optimising industrial structure and enhancing production efficiency significantly reduce carbon emissions and PM2.5 concentration. This suggests that DED promotes PCR governance through the anticipated pathways of industrial structure optimization and production efficiency enhancement, affirming that DE indeed fosters synergistic PCR management.

Table 4

The results of mechanism test

Variables	Model (1)	Model (2)	Model (3)	Model (4)
	<i>IS</i>	<i>TFP</i>	<i>CO₂</i>	<i>PM2.5</i>
<i>DI</i>	1.0238** (2.45)	0.4429*** (5.87)	0.4429*** (5.87)	0.4429*** (5.87)
<i>IS</i>			-0.2105 (-1.07)	0.4429*** (5.87)
<i>TFP</i>			0.4429*** (5.87)	-0.8556** (-4.82)
CV	YES	YES	YES	YES
City-fixed effect	YES	YES	YES	YES
Time-fixed effect	YES	YES	YES	YES
Obs	461	461	461	461
<i>R</i> ²	0.3783	0.2738	0.3245	0.3630

Discussion

Consequently, the study underscores the imperative need to bolster investment in new-generation information and communication technologies (ICT), enhance urban digital infrastructure, and lay the economic groundwork for urban digital transformation. Such measures are deemed essential for advancing the goals of PCR through the DED. Central to

this endeavour is the refinement of mechanisms to incorporate innovative factors, fostering the emergence of model cities for DED through the agglomeration of relevant resources.

Government entities are particularly urged to play a pivotal role in this process. They are called upon to fulfill their responsibilities as service providers by establishing innovation and research platforms conducive to DED advancement. Moreover, governmental support in the form of industrial policies is seen as crucial for fostering DED and facilitating industrial transformation. By offering backing and creating an enabling environment, authorities can catalyse DE growth and facilitate the necessary industrial upgrading essential for effective PCR governance.

In essence, this concerted effort aims to synergise technological innovation, urban development, and industrial transformation in pursuit of sustainable PCR governance. By aligning policies and investments with the imperatives of DED development, stakeholders can collectively contribute to mitigating environmental degradation and fostering economic resilience in the face of contemporary challenges.

Conclusion

This study delves into the practical context of the synergistic effect of PCR, with a specific focus on the DED. It establishes an empirical analysis model utilising city-level panel data spanning from 2011 to 2020. Through this rigorous approach, several key findings emerge. Firstly, the research highlights that DED significantly contributes to the reduction of carbon emissions and PM2.5 concentration, thereby affirming its role in PCR management. These conclusions are reinforced by robustness testing, which underscores the consistent impact of DED on PCR. Moreover, the study reveals that the synergistic effect of PCR resulting from DE development manifests multidimensional heterogeneity. Notably, this effect appears to be stronger in large-scale cities, non-resource-based cities, and economically leading cities. Such variations in the impact of DE development underscore the importance of considering local contexts in implementing PCR strategies. Finally, the research identifies that DED primarily facilitates pollution reduction and carbon synergy by optimising industrial structure and enhancing production efficiency. This finding underscores the multifaceted nature of the relationship between DE development and PCR, emphasising the importance of addressing both environmental and economic considerations in policy formulation and implementation.

Overall, this study contributes to a deeper understanding of the practical dynamics of PCR, shedding light on the role of DED in pollution control and reduction efforts. By elucidating the multidimensional effects of DE development on PCR, the research provides valuable insights for policymakers and stakeholders seeking to design effective strategies for sustainable development.

Reference

- [1] Karlsson M, Alfredsson E, Westling N. Climate policy co-benefits: a review. *Climate Policy*. 2020;20(3):292-316. DOI: 10.1080/14693062.2020.1724070.
- [2] Ürge-Vorsatz D, Herrero ST, Dubash NK, Lecocq F. Measuring the co-benefits of climate change mitigation. *Annual Rev Environ Resources*. 2014;39:549-82. DOI: 10.1146/annurev-environ-031312-125456.
- [3] Mayrhofer JP, Gupta J. The science and politics of co-benefits in climate policy. *Environ Sci Policy*. 2016;57:22-30. DOI: 10.1016/j.envsci.2015.11.005.

-
- [4] Xie Z, Wu R, Wang S. How technological progress affects the carbon emission efficiency? Evidence from National Panel Quantile Regression. *J Cleaner Prod.* 2021;307:127133. DOI: 10.1016/j.jclepro.2021.127133.
- [5] Sun W, Huang C. How does urbanization affect carbon emission efficiency? Evidence from China. *J Cleaner Prod.* 2020;272:122828. DOI: 10.1016/j.jclepro.2020.122828.
- [6] Yu Y, Zhang N. Low-carbon city pilot and carbon emission efficiency: Quasi-experimental evidence from China. *Energy Economics.* 2021;96:105125. DOI: 10.1016/j.eneco.2021.105125.
- [7] Gao P, Yue S, Chen H. Carbon emission efficiency of China's industry sectors: From the perspective of embodied carbon emissions. *J Cleaner Prod.* 2021;283:124655. DOI: 10.1016/j.jclepro.2020.124655.
- [8] Zhu K, Guo X, Zhang Z. Reevaluation of the carbon emissions embodied in global value chains based on an inter-country input-output model with multinational enterprises. *Appl Energy.* 2022;307:118220. DOI: 10.1016/j.apenergy.2021.118220.
- [9] Wu CH, Tsai SB, Liu W, Shao XF, Xia YK, Wacławek M. Green environment and sustainable development: methods and applications. *Ecol Chem Eng S.* 2021;28(4):467-70. DOI: 10.2478/eces-2021-0030.
- [10] Liu W, Tsai SB, Wu CH, Shao X, Wacławek M. Corporate environmental management and sustainable operation: theory and application. *Ecol Chem Eng S.* 2022;29(3):283-5. DOI: 10.2478/eces-2022-0020.
- [11] Filak M, Hoffman S. Benzo(a)pyrene in PM10 - Air monitoring results in Poland. *Ecol Chem Eng S.* 2023;30(4):557-65. DOI: 10.2478/eces-2023-0048.
- [12] O'Neill BC, Dalton M, Fuchs R, Zigova K. Global demographic trends and future carbon emissions. *Proc National Acad Sci.* 2010;107(41):17521-6. DOI: 10.1073/pnas.1004581107.
- [13] Steger U. Environmental management systems: empirical evidence and further perspectives. *Europ Manage J.* 2000;18(1): 23-37. DOI: 10.1016/S0263-2373(99)00066-3.
- [14] Liu W, Tsai SB, Wu CH, Shao XF, Wacławek M. Corporate environmental management with digital transformation: theory and applications. *Ecol Chem Eng S.* 2023;30(2):155-7. DOI: 10.2478/eces-2023-0014.
- [15] Wu SH, Wang HQ, He M, Qin C. Environmental regulation, environmental policy complexity and technological innovation efficiency. *Ecol Chem Eng S.* 2023;30(2):159-66. DOI: 10.2478/eces-2023-0015.
- [16] Wang C, Li J. The evaluation and promoting path of green innovation performance in Chinese pollution intensive industry. *Sustainability.* 2020;12(10):4198. DOI: 10.3390/su12104198.
- [17] Zhou PL, Zhang D, Zhou Q, Xia WJ. Modeling economic performance of interprovincial CO₂ emission reduction quota trading in China. *Appl Energy.* 2013;112(16):1518-28. DOI: 10.1016/j.apenergy.2013.04.013.
- [18] Henneman LRF, Rafaj P, Annegarn HJ, Klausbrückner C. Assessing emissions levels and costs associated with climate and air pollution policies in South Africa. *Energy Policy.* 2016;89(2):160-70. DOI: 10.1016/j.enpol.2015.11.026.
- [19] Zhao B, Wang TY, Jiang Z, Gu Y, Liou KN, Kalandiyur N, et al. Air quality and health co-benefits of different deep decarbonization pathways in California. *Environ Sci Technol.* 2019;53(12):7163-71. DOI: 10.1021/acs.est.9b02385.
- [20] Zhang P, Wu JN. Impact of mandatory targets on PM_{2.5} concentration control in Chinese cities. *J Cleaner Prod.* 2018;197:323-31. DOI: 10.1016/j.jclepro.2018.06.189.
- [21] Wang YP, Yan WL, Ma D, Zhang CL. Carbon emissions and optimal scale of China's manufacturing agglomeration under heterogeneous environmental regulation. *J Cleaner Prod.* 2018;176:140-50. DOI: 10.1016/j.jclepro.2017.12.118.
- [22] Du M, Zhang X, Xia L, Cao L, Zhang Z, Zhang L, et al. The China Carbon Watch (CCW) System: A rapid accounting of household carbon emissions in China at the provincial level. *Renew Sust Energy Rev.* 2021;111825. DOI: 10.1016/j.rser.2021.111825.
- [23] Li FY, Wang Z, Huang LX. Economic growth target and environmental regulation intensity: evidence from 284 cities in China. *Environ Sci Pollut Res.* 2022;29(7):10235-49. DOI: 10.1007/s11356-021-16269-0.