



Nexus among digital inclusive finance and carbon neutrality: Evidence from company-level panel data analysis

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ABSTRACT

This research examined the effects of digital finance and renewable energy investment on carbon neutrality using Chinese companies' panel data from 2005 to 2020 in 30 Chinese provinces. The findings demonstrate that inclusive digital financing may directly lower carbon intensity. It can also impact carbon intensity by enhancing the industrial structure and resource efficiency and encouraging green technologies. The marginal impact of digital financing is lower for big enterprises (larger for small firms). This is in line with the reality that small businesses face more difficulties in accessing finance. Digital finance opens new funding avenues for such businesses to achieve sustainability. The inclusive feature of digital financing, as opposed to conventional banking, may enhance private businesses' green innovation.

1. Introduction

China's economic development over the last quarter century has been phenomenal, making it the world's second-largest economy (World Bank, 2022). However, substantial factor inputs and energy demand levels have followed this expansion, which may cause environmental deterioration and depletion of natural resources (Kordej-De Villa and Slijepcevic, 2019). China now consumes more energy than any other country, and air pollution is a serious problem in most large cities there. There is a more significant proportion of coal to oil in the country's energy consumption. China's economic growth, economic security, and energy security are all significantly threatened by the country's growing reliance on the global energy market, notably the crude oil market, in order to fulfil the country's energy requirements (Liu et al., 2021). Therefore, the Chinese government faces resistance from the energy sector and ecological and national security concerns (Jarrett et al., 2019).

China is at a crossroads on the path to long-term green economic growth. China aims to attain peak carbon emissions by 2030 and achieve net zero emissions by 2060. It is unclear how such a lofty objective can be achieved without dampening economic activity. It is necessary to promote the development of renewable energy and green infrastructure (Taghizadeh-Hesary et al., 2022). While prior research has looked at

green products, much focus has been on how it relates to clean energy R&D (Breen and Hu, 2021). The genuine gauge of green innovation—the finance gap has been little documented in the literature. In addition, a dearth of research experimentally tests whether environmental sustainability and green financing may influence entrepreneurship or whether there is a co-integration between these three concepts (Gong et al., 2020). Governments can benefit from a deeper understanding of the connections between financial inclusion, renewable energy development, and carbon neutrality to enhance resource efficiency for achieving sustainable economic growth.

Further, government investment in renewable energy and digitalization of the financial system can improve ecological and economic growth by implementing policies that promote green innovation and more efficient resource allocation.

Therefore, this research aims to understand better the interplay between digital finance, financial inclusion, and carbon neutrality. In light of this, we are curious about a few things: 1) What effect does the corporate's financial inclusion has on the regional pollution and carbon emissions? Do variations occur between companies' performance? Can there be a third-party effect of microcredit on decreasing cooperative greenhouse gases?

To our knowledge, no research has been conducted on the impact of digitalization and financial inclusion on carbon emissions based on

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company level data in difference regions; hence this is the novelty of our study.

There are substantial contrasts in emissions and financial inclusion among companies in China. However, very few studies have analyzed these differences or the counseling impact mechanism in the influence of financial inclusion on cohesive decarbonization.

The linear regression-based starting points reveal that green growth among listed businesses is greatly enhanced by online financing. Multiple robustness analyses were performed in this study, including those in which the core variables were measured differently, the samples from the banking industry were removed, control variables were added on a regional basis, and the highest prevalence rate was used as the explanatory factor.

The following are the paper's main contributions. This paper clarifies the connection between digital finance and carbon neutrality. Our analysis of yearly panel data reveals that the expansion of digital financial inclusion has a detrimental effect on carbon dioxide emissions. First, we provide a novel and practical method to attain carbon neutrality by thoroughly examining and demonstrating the beneficial impact of digital financial inclusion on carbon neutrality within a thorough both theoretical and empirical paradigm. Second, researchers often emphasize reducing carbon intensity in previous publications about financing supporting low-carbon growth while disregarding carbon capture, which is equally crucial.

This paper considers the various aspects of digital financial inclusion from its inception to its development. This study shows how certain financial features, tools, and regional conditions affect the intensity of carbon emissions and carbon neutrality goals. Digital finance performs better in eastern areas with higher economic variations and high-pollution sectors with higher carbon emissions, according to a heterogeneity study. The inclusive feature of digital financing, as opposed to conventional banking, may enhance private businesses' green innovation, especially in central and western areas and non-high emission sectors. The findings of this research provide factual support for the beneficial role that China's digital finance growth has played in green innovation and serve as a roadmap for major economies across the globe that are working to meet their carbon emission reduction objectives.

The structure of the following parts of the paper is as below:

Section two is on the review of the literature. Section three provides the empirical method and data. Section four is on the empirical results. The last section provides the conclusion and policy recommendations.

2. Literature review

The literature review of this paper is categorized into two subcategories. The first subcategory reviews the studies on the digitalization of the financial system. It tries to show why it is crucial for promoting economic growth and improving environmental quality. Due to the positive effect of digitalization on risk diversification (Tian et al., 2022), digital finance reduces information asymmetric, diminished ex-ante adverse selection, diminishes ex-post opportunities for corruption and optimal resource allocation, and enhances scientific advancement (Y. Y. Wang et al., 2022; Zhao et al., 2022). Financial development and financial inclusion are critical in fostering economic growth and an improved ecological environment. However, some other studies found that financial inclusion results in environmental deterioration. In this middle, Li-Ying et al. (2022) examined the impact of financial inclusion on CO₂ emissions in Asia from 2004 to 2014. They found that financial inclusion appears to have led to higher emissions of CO₂ in the region. No policy synergies were found between financial inclusion and mitigating emissions.

In the second subcategory of the literature review, we looked at the interconnected nature of green transactions, economic growth, and capital formation. Based on the economic theory, more accessible finance by utilizing digital finance boosts economic growth and helps nations increase their total factor productivity (TFP) (Shao et al., 2022).

(Y. J. Wang et al., 2022), recognized the need to address causality, included the instrumental variable of "legal origin" in their model, and concluded that the expansion of financial institutions contributes positively to total factor productivity. These inferences were further bolstered by the findings of (Huang et al., 2021; Tu et al., 2022). However, other studies found that financial literacy and financial inclusion either stifled or had no impact on economic expansion when seen through financial quality, income inequality, and administrative depth.

Several studies have explored the Environmental Kuznets curve (EKC) hypothesis for a single country employing time series data and various models designed to examine measures to account for uncertainty (Zhang et al., 2020; Chan and Dong, 2022). However, contradictory results were found. Due to China's status being one of the world's most rapidly expanding economies, the country has been the site of hot discussions over the EKC for a better future. Guo et al. (2022) discovered that although an ecologically sustainable bleaker cubic connection exists in most experimental Chinese EKC studies, the results are uneven and very different. Very little research has been done on the correlation between several pollutants (such as sulfur dioxide, sludge, etc.) and output compared to the correlation between emissions of CO₂ and production among the various aspects. Furthermore, no agreement has been achieved on establishing the EKC in China due to the diversity of research objectives and methods. This study has three hypotheses that we aim to assess them.

Hypothesis 1. Digital finance makes access to finance easier and results in financial inclusion in sustainability projects.

As was previously said, a lack of capital may be a significant problem preventing businesses from investing in green projects. Technological advancements like big data, Artificial intelligence, and FinTech, significantly reduce the information gap and the asymmetry of information between financial institutions and businesses. It follows that the amount of green investment may increase (Muganyi et al., 2022). Accordingly, we put forward hypothesis 2.

Hypothesis 2. By removing financial barriers, the benefits of digital finance may be fully realized.

An increase in innovation level may be attributed to the increase in talent reservoir and various scientific depths made possible by digital financing in secondary. Additionally, by boosting employment and narrowing the income gap, digital finance contributes to general economic growth and the security of public finances. Consumers' spending on non-essential goods may also be boosted via digital financing. By raising people's living standards by increasing disposable income, we can help them become more productive and content in their daily lives (Song, 2020; Sun et al., 2022a). This shift in the demand structure can motivate scientific research to innovate to boost localized creation. It also contributes to a more nurturing environment for R&D in the area where the business is based. Accordingly, we put forward Hypothesis 3.

Hypothesis 3. Enhancing the degree of localized inventiveness is necessary to realize the benefits of financial innovation.

Macro impacts, such as those on wealth creation, national welfare, and output growth, have been the primary focus of studies examining the consequences of technological infrastructure. (Forsund, 2018), considered technological advances to be a driving force behind regional and national economic development. According to (Akpola and Bakirtas, 2020), the advancement of digitalization has reduced market entity welfare losses, raised production efficiency, and boosted businesses' general well-being. The literature on the economic consequences of public investment in small businesses is sparse. Research in this area has concentrated mainly on the profitability paradox, which focuses on the effects of IT on business output (abbreviated as the productivity paradox). Zhu et al. (2018) contend that the effectiveness paradox has always been present, while Munda and Nardo (2009) keep arguing that

the growth of IT encourages the thorough progression and extensive use of information resources by industries, which can decrease the cost of internal coordination and increase productivity. Information and communications technology (ICT) capital was shown to have a substantial positive link with productivity in a study done by (Betarelli Junior et al., 2021) that included approximately one thousand businesses in Brazil and India.

Recent research has shown the link between financial inclusion and reduced greenhouse gas emissions. For instance (McCartney et al., 2021), looked at the link between banking services and carbon dioxide emissions in China countries and identified a correlation between the two. Twenty-three provinces in China reached a similar conclusion. On the other hand (Ibn-Mohammed et al., 2021; Sun et al., 2022), used panel data to show that the capital market has an EKC influence and draw the opposite conclusion that financial inclusion has a U-shaped association with carbon emissions.

Our study contributes to the literature by considering the size of companies (large size and small and medium-sized). The impact of financial inclusion due to digitalization on the companies' sustainability behavior might differ depending on their size. In addition, we assessed this impact in different provinces of China that consider the level of regional development.

3. Empirical method and data

3.1. Dynamic panel GMM model

We utilize the econometrics techniques and inspired by (Q. Wang and Huang, 2021) and apply the dynamic panel Generalized Method of Moment (GMM) as the primary estimate method.

Creating a dynamic model panel using lagged variables as follows:

$$y_{it} = \alpha_0 + \alpha_1 y_{it-1} + \alpha_2 x_{it} + \alpha_3 control_{it} + v_i + v_t + \varepsilon_{it} \quad (1)$$

y_{it} denotes the dependent variable (carbon emission); x_{it} is the primary explanatory variable (Digital financial inclusion); $control$ is the control variable, and it includes the following: regional GDP, renewable energy investment, digital trade, foreign direct investment, renewable energy policies, and patents; v_i and v_t are the system GMM simultaneously solves the endogeneity issue (Bai and Dahl, 2018) and the dilemma of weak parameter estimates, ε_{it} denotes the residuals.

3.2. Nonlinear model of panel threshold

We use the instrumental variable model introduced by (Neralić and Kedžo, 2019). The underlying assets for estimating panel data models are as bellow:

$$y_{it} = \alpha_i + Z_{it}\delta + 1(q_{it} \leq \gamma)X'_{it}\beta_1 + 1(q_{it} > \gamma)X'_{it}\beta_2 + \varepsilon_{it} \quad (2)$$

$$1(q_{it} \leq \gamma) = \begin{cases} 1 & \text{if } q_{it} \leq \gamma \\ 0 & \text{if } q_{it} > \gamma \end{cases}; 1(q_{it} > \gamma) = \begin{cases} 0 & \text{if } q_{it} \leq \gamma \\ 1 & \text{if } q_{it} > \gamma \end{cases}; \varepsilon_{it} \quad (3)$$

For a threshold-based estimate, we first take the mean of the previous and then remove the prototype from the mean.

The initial hypothesis was that $H_0: = 0$ does not include a barrier. It implies a mixed result, calling for an investigation into the barrier and significance value. Tests of the crucial and thresholds values are conducted using the Likelihood-ratio test (LR) statistic developed by (Kaa-keh et al., 2021) as in Eq. (4):

$$LR(\gamma) = \frac{RSS(\gamma) - RSS(\bar{\gamma})}{RSS(\bar{\gamma})/N(T-1)} \quad (4)$$

When no threshold effect is present, the sum of residue squaring of the bounds test is denoted by the Residual Sum of Squares (RSS), and when a threshold influence is present, it is denoted by RSS.

3.3. The quantile regression

The idea of using parametric estimates to investigate the connection between the unconditional expectancy of X and Y was conceived by (Marttunen and Mustajoki, 2018). We implement the linear regression panel model with explanatory variables for this aim.

The regression model is helpful because it displays the effect factor of the variable just on dependent variables and is robust to outliers (Gao, 2020). An approximations equation would look like this:

$$Q_{Y|X}(\tau) = X'\beta(\tau) \quad (5)$$

$$Y_{it} = F_{it}\beta(\mu_{it}^*), \mu_{it}^* \sim \mu(0, 1) \quad (6)$$

Suppose we want that the fixed-effects coefficient remains static between data points but that the estimated coefficient of the predictor variables changes across deciles. In that case, we can state the optimal solution as in Eq. (7):

$$\min_{b \in B} \sum_{i=1}^n \rho_{\tau}(Y_i - X'_i b) \quad (7)$$

The characteristics $b \in B$ are represented by the random selection X_i , Y_i , where $i = 1, 2, \dots, n$. In particular, the function signifies the typical test value. A regression estimate is performed by minimizing this function (U.S. Energy Information Administration, 2017). Like other nonlinear models, regression benefits from increased data and may display the effectiveness at varying quantiles using the panel threshold.

3.4. Data

We use the Chinese company-level annual data for solar, wind, and hydropower. The following variables are chosen depending on the logic and economies of control variable data. Demographic and urban rates are proxies for the number of people and the size of the company that might work for showing if the impact depends on the size of the company. Renewable energy investment is used as a control variable. Digital trade is another control variable. Regional GDP shows the provincial output. Direct investments from abroad (FDI) is a capital investment that may be received via trade and other forms of capital inflows (OFDI).

4. Empirical results

Important scores on dependent factors with a lag of one year reveal the dynamic nature of a company's economic success in green business. Beneficial and substantial impacts of digital finance are supported, providing evidence for H1. In line with previous research, financial constraints negatively affect financial performance. Higher financial expenses and limits might reduce productivity. Similarly, the influence of digital finance will be hampered by a lack of financial resources (Yudarwati and Gregory, 2022). For the adoption of sophisticated digital technology, there is a need for digital elites and the need for economic and human resources (H2).

The static model is first estimated as a baseline before the panel data is estimated. Whether or not the control factors are involved, the findings show that digital finance impacts economic growth positively, and economic constraint harms financial performance, suggesting H1 and H2. There is no moderating effect of financial limitation in the static model, as shown by the lack of significance of the association term.

For a company's bottom line, technology is crucial (H3). Since innovation may serve as a confounding variable between digital finance and economic constraint and financial success, it is not accounted for in the above research (Franco and Landini, 2022). However, for further robustness testing, R&D intensity may be accounted. Table 1 is a summary of the empirical findings. The results show that inclusive digital finance (FIN), investments in renewable energy (REN) projects, and digital trade (DTR) reduce carbon emissions. The findings are in line

Table 1
Results of Cup-FM, Cup-BC, and system GMM.

Dependent Variable: CAR						
Variables	CUP-FM		Cup-BC		Sys-GMM	
	Coefficient	t-statistics	Coefficient	t-statistics	Coefficient	t-statistics
CAR _{t-1}	–	–	–	–	0.266***	3.374
GDP	0.654***	4.787	0.476***	4.234	0.364***	2.785
FIN	–0.456***	–6.198	–0.298***	–5.743	–0.087**	–2.356
DTR	–0.764***	–4.832	–0.267***	–5.098	–0.187**	–2.134
REN	–0.387***	–10.598	–0.386***	–11.552	–0.298***	–3.865

Source: Authors' calculations; Note: *** and ** Significant value at 1% and 5% level of significance; CAR=Carbon emission; GDP = Provincial economic growth, FIN = Digital financial inclusion, DTR = Digital trade, REN = Investment in Renewable energy; CUP-FM = continuously updated fully modified; CUP-BC = continuously updated bias-corrected.

with the results of Wang J. et al. (2022) and Cao et al. (2021) for China, who found that the digital economy affects CO₂ emissions in China via scale, structure, and technical effects.

We have made the threshold selection based on the bootstrap method. The results are provided in Table 2. According to the findings, the marginal impact of digital financing is lower for big enterprises (larger for small firms). This is in keeping with the reality that small businesses face more financial risks and that digital finance opens up new (Li-Ying et al., 2022) funding avenues for such businesses to achieve greenness.

Financial constraints negatively impact small businesses more than large enterprises. Small businesses lack enough collateral and transparent financial statements; hence, borrowing from banks is difficult. Banks or other lending institutions can not assess the risk of small and medium-sized businesses (SMEs); hence they refuse to lend to them. This is more significant for loans to green projects, as banks consider green projects risky. Banks consider green projects risky because the rate of return in these projects is lower compared with many other projects. Hence policies are needed to facilitate SMEs' access to green projects loan. Digitalizing the financial system can reduce information asymmetry and make lending to SMEs easier, including loans for green projects.

5. Conclusion and policy recommendations

In order to evaluate the impact of digital finance on companies' carbon emissions and study the impact mechanism of inclusive digital finance on carbon neutrality from the sustainable economic growth effect, this research utilizes Chinese company-level data from 2005 to 2020. The findings indicate that corporate carbon emissions are reducing by digital financing. In particular, the effect of digital financial inclusion on boosting carbon sequestration is decreasing while reducing

carbon intensity, with the marginal impact first weakening and then strengthening.

Second, the marginal impact of digital financing is lower for big enterprises (larger for small firms). This is inline with the reality that small businesses face more difficulties in accessing finance that; digital finance opens up new funding routes for businesses to achieve greenness and reduce their carbon footprint.

Third, at the moment, the breadth of coverage favorably encourages a rise in carbon sequestration while the depth of use mostly supports decreasing carbon intensity. Payment, credit, insurance, and investment are the four main financial tools that play different roles in this process.

Fourth, in cities with numerous financial dimensions, the consequences of digital financial inclusion on carbon intensity and carbon sequestration vary. Furthermore, the former is found in big cities, whereas the latter is found in big and small cities.

Lastly, cities with a high reliance on resources may reduce their carbon intensity more than other cities. However, there is no discernible difference when it comes to carbon sequestration.

This study provides some helpful policy recommendations for its continued growth in light of the fundamental finding that attaining digital financial inclusion is advantageous for reaching carbon neutrality.

- From a macro perspective, the central and local governments should continue to execute and enhance digital financial inclusion plans and build a robust, stable financial system with a corresponding regulatory framework.
- In order to increase the capacity to absorb capital and thereby develop a sizeable financial market, the advancement of digital financial inclusion should also consider regional economic conditions, industry types, and infrastructure levels.
- It should also place equal emphasis on quantity and quality. It should also keep financial construction as its focal point.
- Another idea is to strengthen the infrastructure built for financial products and digitalization, which may aid in extending the global audience.
- The government may provide tax cuts and financial subsidies to companies that promote digital financial inclusion, particularly to small and medium-sized enterprises (SMEs) in urban and rural regions. In addition, charging carbon taxation on polluting enterprises and injecting the collected taxes into the green SMEs that use digital technologies would be another supporting policy (Yoshino et al., 2021).
- By using the power of the government, grassroots activists may aid in spreading awareness of financial technology inclusion in less developed regions and boosting its acceptability.
- To avoid the creation of distortions, it is crucial for the government to gradually develop and execute the policies mentioned above and without being extreme but rather pragmatic.

Although the research presented in this paper partially fills in the

Table 2
Threshold regression results.

Variable	Car_I			Car_S	
	Var = DIF	Var = SSTE	Var = OPEN	Var = DIF	Var = HE
DIF * I (Var < Q ₁)	–0.290*** (0.061)	–0.070 (0.049)	–0.191*** (0.060)	0.103*** (0.041)	0.039 (0.041)
DIF * I (Q ₁ ≤ Var < Q ₂ or Var ≥ Q ₁)	–0.261*** (0.060)	–0.131** (0.048)	–0.190*** (0.061)	0.080** (0.041)	0.031 (0.041)
DIF * I (Var ≥ Q ₂)	–0.290*** (0.060)	–0.166*** (0.048)	–0.177*** (0.048)	0.061* (0.041)	
Control variables	YES	YES	YES	YES	YES
Individual FE	YES	YES	YES	YES	YES
Time FE	YES	YES	YES	YES	YES
R ²	0.432	0.432	0.432	0.141	0.131
N	2040	2040	2040	2040	2040

Source: Authors' calculations.

gaps in the literature concerning the influence of digital financial inclusion on carbon neutrality, some shortcomings still need to be investigated and corrected. These shortcomings can serve as a guide for future research in related fields. First, study findings indicate that the effect of digital financial inclusion on carbon sequestration is waning and that there is no discernible pulling force. However, it is uncertain if the influence is sustained, vanish, or increases in the future owing to the absence of data on carbon sequestration. The index, however, has an inherent weakness in that it only utilizes Alipay as a reference while ignoring banks and WeChat, the other two industry titans in digital financial inclusion. Future studies should look at creating a more accurate and complete digital financial inclusion index.

Declaration of competing interest

We confirm that the manuscript has been read and approved by all named authors and that there are no other persons who satisfied the criteria for authorship but are not listed. We further confirm that the order of authors listed in the manuscript has been approved by all the authors. We declare that there is no conflict of interest.

Data availability

The authors do not have permission to share data.

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