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DIGITAL EMPOWERMENT AND ENTERPRISE CARBON RISK MANAGEMENT: EVIDENCE FROM MANUFACTURING SECTOR

Abstract: The paper addresses the imperative of empowering enterprises to achieve energy savings and emission reductions through digital development amidst the backdrop of peak carbon dioxide emissions and carbon neutrality. This study integrates digital empowerment and enterprise carbon risk management into a unified analytical framework, utilising panel data from listed companies spanning from 2011 to 2020 as research samples. The empirical investigation aims to ascertain whether there exist carbon risks impacting the operational performance of manufacturing enterprises and whether digital empowerment can mitigate these risks. The findings reveal that carbon intensity exerts an inhibitory influence on the enhancement of enterprise performance, indicating the presence of carbon risk issues faced by enterprises. Furthermore, it is observed that these carbon risk challenges escalate over time, a trend supported by robustness tests. Digital empowerment emerges as an effective mechanism in slowing down the carbon risks encountered by enterprises, albeit exhibiting characteristics of time lag. The study identifies notable heterogeneity in the role of digital empowerment in mitigating the carbon risks of enterprises.

Keywords: carbon intensity, business performance, digital empowerment, carbon risk, manufacturing industry

Introduction

China stands amidst a green transformation, wherein the escalating strictness of environmental regulations imposes considerable costs for emission reduction upon high-polluting industries. Consequently, embracing high-quality development necessitates departing from conventional models characterised by energy-intensive, pollution-heavy, and high-yield growth. Instead, it calls for a more intensive and innovative low-carbon developmental paradigm, rooted in the principles of energy conservation, eco-friendliness, and heightened efficiency. Within the scope of the "dual carbon" objectives of carbon peaking and carbon neutrality, the imperative of strengthening carbon risk management looms large for effectively achieving emission reduction targets. Carbon risk refers to the financial, regulatory, and operational risks that businesses and investors face due to the transition to a low-carbon economy. On one hand, it arises due to the implementation of carbon reduction regulations, exacerbating risks associated with industrial transformation and severe contraction of financial assets. On the other hand, it stems from fluctuating capital market performance and unstable cash flows of enterprises, driven by uncertainties surrounding carbon control regulations, inadequate compliance by companies, and a lack of awareness regarding low-carbon management.

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However, practical experience in carbon risk management remains deficient, and policy tools for such management are singular and costly. Consequently, a gap often emerges between the emission reduction activities of numerous enterprises and their carbon risk management, resulting in unsatisfactory business operations. Hence, the pursuit of a win-win scenario - integrating energy conservation and emission reduction with quality and efficiency improvement - through internal carbon risk management in a complex and ever-evolving environment assumes paramount significance for enterprise development.

In theory, digital empowerment has the potential to facilitate the digitised management of carbon emissions, deepen the application of low-carbon energy-saving digital technologies, and mitigate carbon risk through carbon reduction. Leveraging digital service platforms, enterprises can conduct in-depth exploration and real-time monitoring of data related to energy production, transportation, and utilisation, thereby achieving rational planning and control of energy service activities, avoiding energy wastage across multiple stages. Simultaneously, real-time monitoring of carbon emissions in various production processes and departments can be realised, and carbon reduction decision optimisation can be achieved through big data services. Digital technology not only effectively substitutes traditional production techniques and innovates energy utilisation patterns to reduce carbon emissions from the production end but also maximises positive externalities based on the connectivity advantages and strong spill-over characteristics of digital technology, thereby reinforcing the synergistic effects of industry-wide emission reduction. Specifically, digital empowerment characterised by the application of technologies such as big data, cloud computing, and artificial intelligence contributes to decision optimisation in enterprises, enabling timely and effective monitoring and management of transactions, production, and transportation of energy and other production factors. By building an energy service network based on the internet, digital empowerment facilitates efficient allocation of energy resources among enterprises and departments. Furthermore, digital empowerment enables energy automation production through program settings, optimises production scale and product variety based on market data and customer feedback, reduces overcapacity and energy wastage, thus assisting in achieving energy-saving and emission reduction goals for enterprises. Therefore, this paper anticipates that digital empowerment will be beneficial for carbon reduction in enterprises, thereby aiding in alleviating potential carbon risk issues they may face.

While significant attention has been directed towards examining the economic consequences of corporate digital empowerment, there remains a dearth of studies exploring its environmental implications at the micro level. Against the backdrop of the ongoing low-carbon transition and the rapid expansion of the digital economy, investigating this question holds paramount theoretical significance and practical relevance. Addressing this inquiry within the scope of this paper will enable a precise assessment of the energy-saving and developmental impacts of enterprise digital empowerment at the micro level.

Literature review

Carbon risk evaluation

Carbon risk, characterised as a quintessential environmental hazard, is precisely defined as "the uncertainty stemming from the utilisation of fossil fuels and emissions of greenhouse gases concerning enterprise production and operational activities" [1, 2].

Significantly, diverse industries and sectors encounter varied manifestations of carbon risk, with energy-dependent sectors such as energy enterprises often contending with more pronounced carbon risk predicaments. Therefore, for high-carbon-emitting enterprises, enhancing the carbon risk assessment mechanism and formulating effective countermeasures assumes considerable importance.

Currently, numerous scholars have undertaken a more comprehensive investigation by integrating agency theory, risk management theory, and other facets of carbon risk management. This research encompasses two principal categories: Firstly, the identification and assessment of carbon risk [3, 4]. Given the scarcity of corporate environmental information disclosure and the challenge of obtaining micro-environmental data, the questionnaire method has found wide application in evaluating corporate carbon risk. Specifically, the CDP questionnaire is tailored to assess corporate awareness of carbon risk. Jung et al. [4] directly assessed corporations' carbon risk awareness by analysing their responses to the CDP questionnaire. Additionally, some scholars utilise the intensity of low-carbon technological innovation input as an inverse characterisation of carbon risk [5].

Furthermore, the impact of carbon risk on enterprises' production, operations, and innovation activities is scrutinised. Data derived from the capital market affirm that carbon risk management profoundly affects enterprises' capital costs, financial performance, and enterprise value. On one hand, prospective carbon risk can foster complacency among enterprises and heighten the importance of green innovation technology [6]. For instance, Dumrose and Hock [7] found that heightened carbon risk awareness significantly promotes low-carbon innovation, thereby enhancing productivity and carbon performance. On the other hand, carbon risk can be perceived as pressure on enterprises to reduce carbon emissions within established production and operational capacities, often accompanied by increased agency costs and compliance expenses, thus inhibiting long-term development [8, 9].

Digital empowerment affects environmental quality

Digital empowerment encapsulates the process of infusing enterprises' production, operations, and management with digital technology to revolutionise their original mode of operation [10]. Currently, research on the impact of digital development on enterprise production and innovation has yielded pivotal and insightful findings. At a macro level, digital advancement, exemplified by the widespread adoption of the Internet and the establishment of digital infrastructure, promotes regional innovative integration and strengthens innovation capabilities. At a micro level, the adoption of digital technologies such as cloud computing and blockchain enhances organisational management optimisation and empowers technological research and development. Furthermore, digital empowerment influences various facets of enterprises, including product design [11, 12], process flow [13, 14], and decision-making [15, 16]. The deep integration of the digital economy with traditional industries further underscores how digital empowerment, grounded in digital technology application, artificial intelligence development, and digital investment, inevitably impacts enterprises' efforts in energy conservation and emission reduction.

Despite the critical role of carbon risk in enterprise operations, few studies have empirically examined whether enterprises encounter such risks in their operations. Building upon the empirical examination of whether enterprises' business performance faces carbon risk, this paper endeavours to delve into the underlying rationale behind how digital

empowerment can mitigate enterprises' carbon risk. Ultimately, the aim is to provide empirical guidance on digital empowerment and carbon risk management for enterprises.

Empirical methods

Model design

Based on the theoretical analysis presented above, this paper constructs the following model to test whether business operations encounter carbon risk:

$$ROA_{it} = \alpha_0 + \alpha_1 CE_{it} + \alpha_2 X + \nu_j + \lambda_t + \varepsilon_{it} \quad (1)$$

where i denotes firm, t - year, j - industry, and ROA_{it} - enterprise business performance, and CE_{it} - enterprise carbon intensity; α_0 - the constant term, and α_1 and α_2 - the coefficients to be estimated, if $\alpha_1 < 0$, then it indicates that carbon intensity inhibits the improvement of business performance, i.e., the business operation faces carbon risk. ν_j and λ_t - industry dummy variables and year dummy variables, and ε_{it} - the random disturbance term, X - the control variable.

Moreover, to scrutinise whether digital empowerment effectively mitigates the carbon risk confronted by firms, this study formulates an interaction term between digital empowerment and carbon intensity. Subsequently, the interaction term, along with digital empowerment, is integrated into a benchmark regression model, as outlined below:

$$ROA_{it} = \alpha_0 + \alpha_1 IE_{it} + \alpha_2 CE_{it} + \alpha_3 CE_{it} \times IE_{it} + \alpha_4 X + \nu_j + \lambda_t + \varepsilon_{it} \quad (2)$$

where IE_{it} denotes the numeric assignment variable, and α_0 - the constant term, and α_1 to α_4 - the coefficient to be estimated.

Description of data sources and indicators

The selection of panel data from Chinese A-share manufacturing companies spanning the period from 2011 to 2020 constitutes a methodological choice that significantly enhances the depth and breadth of research into carbon risks and digital empowerment within this sector. By adopting a longitudinal approach, researchers gain the ability to observe changes and developments within the same companies over an extended timeframe, allowing for the identification of trends, patterns, and potential causal relationships. This longitudinal analysis is crucial for understanding the evolution of carbon risk management strategies and the adoption of digital technologies within the context of Chinese manufacturing firms.

Moreover, the considerable sample size of 10,037 observations lends robustness to the study's findings and enhances the generalisability of its conclusions. Focusing specifically on A-share companies listed on the Shanghai and Shenzhen stock exchanges ensures representation from a significant portion of the Chinese manufacturing sector, thereby bolstering the external validity of the research. This approach acknowledges the importance of studying a diverse range of companies operating within a specific industry and geographical context to gain a comprehensive understanding of the phenomena under investigation.

The primary data sources utilised in this research, including annual reports of enterprises, as well as the Wind database and Guotaian database, offer rich and detailed information on various aspects of corporate activities, financial metrics, and market dynamics. These sources provide valuable insights into companies' sustainability

initiatives, efforts to mitigate carbon risks, and adoption of digital technologies. Leveraging multiple data streams enriches the analysis and enables researchers to explore the complex interplay between environmental sustainability practices and technological innovation within the Chinese manufacturing landscape.

The specific descriptions of the pertinent indicators are as follows:

(1) Corporate operating performance (*ROA*): This metric gauges business performance by computing the ratio of the company's net profit at the end of the year to its total assets. The total assets of the company are represented as the average of the total assets at the end of the year and the total assets at the beginning of the year.

(2) Corporate carbon intensity (*CE*): This paper employs energy consumption data disclosed in annual reports to roughly estimate total carbon emissions for enterprises. Subsequently, the carbon intensity of enterprises is depicted using the ratio of total carbon emissions to main business income.

(3) Enterprise digital empowerment (*IE*): Diverging from prior studies that focused solely on digital financial inclusion, the Internet, or industrial intelligence, this paper assesses the level of enterprise digital empowerment through word frequency statistics of various digital empowerment-related words that appear in the annual reports of enterprises.

(4) The paper incorporates a set of enterprise-level control variables based on the studies of Wu et al. [17] and Jiang [18]. These control variables include: Enterprise size (*Size*): Represented by the logarithm of the number of employees in the enterprise. Age of the enterprise (*Age*): Calculated as the current year minus the year of the establishment of the enterprise, plus 1. Gearing ratio (*Leverage*): Indicated by the ratio of total liabilities to total assets. Liquidity ratio (*Liquid*): Expressed as the ratio of current assets to total assets. High-tech attributes (*Hte*): Categorised as 1 if the enterprise is recognised as a high-tech enterprise; otherwise, it is set to 0. Ownership attribute (*Nature*): Set as 1 if the enterprise is state-owned; otherwise, it is set to 0.

Empirical results

Existence test for corporate carbon risk

Table 1 presents the impact of firms' carbon intensity on their own business performance, estimated using the Ordinary Least Squares (OLS) method. The table comprises three columns with different specifications. The results reveal that the regression coefficients of enterprise carbon intensity (*CE*) on business performance are all negative, and they all pass the significance test at a 1 % confidence level. This indicates that an increase in enterprise carbon intensity results in a significant decline in its own business performance, suggesting that the enterprise's business is indeed facing carbon risk. Importantly, this conclusion holds even after accounting for the relevant set of control variables. Additionally, the estimation results of the other control variables indicate that enterprise size and enterprise age have significantly positive effects on business performance. This implies that as enterprises mature and expand in scale, their ability to cope with various business risks improves, resulting in enhanced overall performance [19, 20]. However, both enterprise leverage and ownership nature exhibit significantly negative impacts on corporate performance, indicating that when the leverage ratio of a company is excessively high, its operational performance tends to be subpar.

Furthermore, compared to non-state-owned enterprises, state-owned enterprises demonstrate relatively poorer operational performance.

Table 1

Existence test of enterprise carbon risk

Variables	Model (1)	Model (2)	Model (3)
CE	–0.1178*** (–5.88)	–0.2099*** (–5.96)	–0.1872*** (–5.74)
lnsise		0.0050** (5.02)	0.0047* (4.67)
age		0.0003* (8.22)	0.0004** (6.40)
Leverage		–0.0376*** (–4.44)	–0.0244*** (–5.32)
Nature		–0.0060** (–2.32)	–0.0048** (–2.34)
Hte		–0.0001 (–0.08)	–0.0010 (–0.66)
Liquid		–0.0002 (–0.54)	–0.0002 (–0.70)
Industry/year dummy variable	YES	NO	YES
Obs	10037	10037	10037
R^2	0.1278	0.1038	0.1814

Note: ***, ** and * indicate that they have passed the significance test of 1 %, 5 % and 10 %. The value of *t* is in brackets. R^2 represents the fit coefficient of the model

The role of digital enablement in mitigating corporate carbon risk

Table 2 presents the outcomes of model (2) derived from the estimation utilising the OLS method. Evidently, the estimated coefficient for digital empowerment (*IE*) impacting firms' business performance exhibits a statistically significant positive value, implying a direct and favourable influence of digital empowerment on firms' business performance. Additionally, the estimated coefficients for the interaction terms involving digital empowerment and carbon intensity (*IE* × *CE*) also demonstrate statistically significant positive values. This intriguingly indicates that the impact of enterprises' carbon intensity on their own business performance transitions from negative to positive under the combined effect of digital empowerment.

To elucidate further, digital empowerment plays a pivotal role in mitigating the carbon risk encountered by business operations. This phenomenon can be attributed partly to the technological innovation attributes of digital empowerment and partly to the amplified efficiency of production decisions facilitated by it.

Table 2

Impact of digital empowerment on carbon risk of enterprises

Variables	Model (1)	Model (2)	Model (3)
IE	–0.1301*** (–4.61)	–0.1942*** (–3.88)	–0.1972*** (–4.55)
CE	0.4618*** (3.80)	0.5514*** (6.03)	0.4298*** (5.12)
IE × *CE*	0.0073** (2.04)	0.0052** (2.11)	0.0058** (2.35)
lnsise		0.0040* (4.50)	0.0053** (4.97)
age		0.0005** (6.31)	0.0004* (8.13)
Leverage		–0.0275*** (–5.20)	–0.0322*** (–4.19)
Nature		–0.0044** (–2.41)	–0.0066** (–2.40)
Hte		–0.0013 (–0.84)	–0.0008 (–0.24)
Liquid		–0.0002 (–0.75)	–0.0003 (–0.39)
Industry/year dummy variable	YES	NO	YES
Obs	10037	10037	10037
R^2	0.1781	0.1438	0.1007

In addition, we further examines the dynamic characteristics of the mitigating effect of digital empowerment on corporate carbon risk over time. The results, as presented in Table 3, indicate that the estimated coefficients of the interaction term between digital empowerment and carbon intensity are not significant in the first and second lag periods, only becoming significantly positive in the third lag period. This suggests that while digital empowerment benefits in alleviating the carbon risk faced by enterprises, this positive impact is not immediate; rather, it exhibits a certain lag. As the level of digital empowerment continues to increase, the mitigating effect of digital empowerment on corporate carbon risk will gradually manifest over time and continue to strengthen.

Table 3

Dynamic characteristics of carbon risk mitigation by digital empowerment

Variables	**Model (1)**	**Model (2)**	**Model (3)**	**Model (4)**
L1. CE × IE	0.0060(1.38)			
L2. CE × IE		0.0069(1.24)		
L3. CE × IE			0.0071***(2.98)	
L4. CE × IE				0.0083***(5.44)
Control variables	YES	YES	YES	YES
Industry/year dummy variable	YES	YES	YES	YES
Obs	8455	7064	5716	4722
R^2	0.1409	0.1515	0.1256	0.1589

Robustness analysis

To ensure the robustness and credibility of the estimation findings, this study implements various robustness analysis techniques, as detailed in Table 4.

Model (1) involves the substitution of explanatory variables. In this paper, the continuous variable of digital empowerment is discretised into two groups: those with a higher degree of transformation (*IE* = 1) and those with a lower degree of transformation (*IE* = 0), based on the median value of the digital empowerment index. Remarkably, the outcomes in Model (1) align with the earlier benchmark conclusions, reinforcing the reliability of the initial results. Model (2) focuses on excluding contemporaneous policy disturbances. Hence, this paper undertakes a re-estimation, excluding the carbon trading policy pilot from the analysis. Encouragingly, even after eliminating the interference of contemporaneous policies, the results in Model (2) demonstrate that digital empowerment continues to play a significant role in alleviating the carbon risk confronted by enterprises.

Table 4

Robustness analysis

Variables	**Model (1)**	**Model (2)**
	Replace explanatory variables	Eliminate policy interference in the same period
CE × IE		0.0064*** (3.73)
CE × IE-01	0.0031**(2.50)	
Control variables	YES	YES
Industry/year dummy variable	YES	YES
Obs	10037	8131
R^2	0.1775	0.1306

Heterogeneity analysis

This research delves into the heterogeneous aspects of digital empowerment's impact on corporate carbon risk. The investigation considers ownership attributes as dimensions of analysis. The pertinent findings are presented in Table 5.

The findings indicate that digital empowerment insignificantly influences the carbon risk of both start-up and mature enterprises. Conversely, there is a notably negative impact on the carbon risk of growth-stage enterprises. This suggests that the energy-saving and emission-reducing benefits facilitated by digital empowerment are predominantly concentrated in growth-stage enterprises. To summarise, this study reveals distinct characteristics in the mitigation effect of digital empowerment on corporate carbon risk, emphasising the unique influence of ownership attributes, high-technology attributes, and the life cycle of enterprises. These insightful findings contribute to a more nuanced comprehension of the role of digital empowerment in fostering sustainable practices across various types and stages of enterprises.

Table 5

Characteristics of carbon risk heterogeneity among enterprises embracing digital empowerment for slow-release mechanisms

Variables	**Model (1)**	**Model (2)**	**Model (3)**	**Model (4)**
	State-owned enterprises	Non-state-owned enterprises	High-tech enterprises and	Non-high-tech enterprises
CE × *IE*	0.0045 (0.93)	0.0068*** (4.28)	0.0056* (1.91)	0.0062*** (3.90)
Obs	5328	4709	3970	6067
R^2	0.1580	0.2037	0.1940	0.1951

Conclusion

This paper delves into the veracity of carbon risk management in enterprises amid the "dual-carbon" objective, scrutinising the presence of carbon risk at the microcosmic level of these organisations. Subsequently, it investigates whether digital empowerment can be instrumental in ameliorating the carbon risk encountered by enterprises. Carbon intensity substantially hampers the operational performance of manufacturing enterprises, revealing their exposure to carbon risk. Temporally, the issue of carbon risk confronting business operations is on the rise. Moreover, digital empowerment aids in mitigating the carbon risk confronting business operations. Nonetheless, the effect of digital empowerment on carbon risk mitigation is not instantaneous but entails a certain delay. Substantiating evidence from the robustness test bolsters this assertion. Additionally, the process of mitigating carbon risk through digital empowerment is not an expeditious one. The efficacy of energy efficiency enhancement due to digital empowerment exhibits distinctive dynamic superposition attributes, necessitating the long-term promotion and implementation of digital empowerment strategies.

The government should continually enhance the institutional environment for digital empowerment, deepen institutional reform, and actively encourage and facilitate enterprise digitalisation. Firstly, given that the development of the digital economy provides an opportune moment for traditional enterprises to transition into function-oriented service enterprises, the government should intensify policy support for enterprise digital empowerment. This entails actively introducing targeted financial and tax subsidy policies to alleviate the cost burden associated with digital empowerment for enterprises.

Additionally, the government should take the lead in constructing big data platforms and sharing factories, leveraging digital service means to facilitate the sharing of production resources and promote the circulation of production factors, thereby reducing unnecessary energy waste in the production processes of enterprises. Secondly, the government should expedite the establishment of relevant systems for data resource rights confirmation, openness, circulation, and transactions, while strengthening intellectual property protection for digital technology and data assets to maintain the proactive development of enterprise data. Lastly, given that enterprise digital empowerment requires support from diverse elements, the government should refine the supply system for various service elements such as technology, information, management, consulting, finance, and human resources, laying the external environmental foundation for fully leveraging digital empowerment to mitigate corporate carbon risk.

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