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Establishment of Big Data pilot Zone and Its Impact on Corporate Green Performance

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Abstract Based on the dataset of 2,207 listed companies in the A-share market of Shanghai and Shenzhen from 2012 to 2022, on the basis of constructing a national big data comprehensive pilot zone, this study combines multiple period Difference-in-Differences (DID) model and fixed-effects model to deeply explore the specific impact of this pilot zone on the green performance of enterprises and its mechanism. Through rigorous parallel trend tests, placebo tests, and robustness tests, the big data comprehensive pilot zone has shown significant effectiveness in improving the level of enterprise green performance. Mechanism analysis indicates that reducing the average tenure of senior executives, shortening the credit term structure, and enhancing the level of digital development can positively incentivize the development of enterprise green performance. Furthermore, the establishment of the big data comprehensive pilot zone to promote enterprise innovation shows heterogeneity. This study finds that the policy effect of the big data comprehensive pilot area in empowering enterprise green performance is more significant in high-tech industries and non-innovative provinces and non-state-owned enterprises. This study helps to clarify the impact of the construction of the big data comprehensive pilot zone on enterprise green performance, providing theoretical support and policy recommendations for driving enterprise green innovation and improving enterprise green performance through digitization in China.

Index Terms Big Data, Big Data Comprehensive pilot Zone, Green Performance, Difference-in-Differences Model

I. Introduction

With the rapid advancement of information technology and the accelerating process of digital transformation, big data has gradually become a strategic resource in the new era, carrying the significant mission of leading innovation and driving development. It has gradually penetrated various fields of the social economy and plays an increasingly important role. In the current context, in September 2015, the State Council of China officially launched the construction of Guizhou Province as a comprehensive big data pilot zone, and later in October 2016, approved key regions such as Beijing-Tianjin-Hebei, the Pearl River Delta, Shanghai, Chongqing, Shenyang, and Inner Mongolia for the development of big data. In 2018, the State Council officially issued the "Outline of the National Digital Economy Development Strategy," which clearly outlines the systematic strategic deployment of our country's digital economic development infrastructure and services. The "14th Five-Year Plan for Digital Economy Development" released in 2022 has clearly defined the overall train of thought, development goals, and key tasks for the development of our country's digital economy from a top-level design. The "Overall Layout Plan for Digital China Construction" released in 2023 provides a clear strategic deployment for building Digital China. The establishment of comprehensive big data pilot zones not only provides a broad platform for the aggregation, circulation, and application of data but also offers new opportunities for innovation and transformation of enterprises.

In the new development pattern of accelerating the green transformation, knowledge, information, data, and technology serve as the main driving forces for economic development. Data, as a key restructured resource element, provides important support for high-quality economic development. The 20th National Congress of the Communist Party of China emphasized that sustainable economic development cannot be achieved without the green transformation of the economic development mode. Enterprises, as the main force affecting economic development, also need to continuously innovate green technologies in their production and operation activities to promote the development of green performance. The improvement of green performance not only helps enterprises reduce resource consumption and environmental pollution, achieve a win-win situation of economic and environmental benefits, but also enhances enterprises' sense of social responsibility and brand image, winning more market recognition and support for enterprises.

The establishment of a comprehensive big data pilot zone provides powerful support for enterprises to acquire, analyze, and apply big data. By leveraging the in-depth exploration and detailed analysis of big data, enterprises can more accurately

capture market dynamics, optimize production processes, thereby further enhancing product quality and competitiveness, and ultimately achieving an improvement in green performance. At the same time, big data can also help enterprises monitor and manage environmental risks, formulate more scientifically reasonable environmental protection measures, and reduce adverse impacts on the environment.

However, the impact of the comprehensive big data pilot zone on the green performance of companies is not achieved overnight. In practical operation, companies also need to overcome a series of challenges such as low data quality, data security risks, talent shortage, and more. Furthermore, how to integrate big data technology with the company's green development strategy to maximize the application of big data in enhancing the company's green performance is also a pressing issue to be addressed. Therefore, this study aims to explore in depth the impact mechanism and operational path of the establishment of a comprehensive big data pilot zone on the green performance of companies. We consider the comprehensive big data pilot zone as an external shock factor and use a quasi-natural pilot method to construct a difference-in-differences model for an in-depth study. The study analyzes the impact on the company's green performance, examines the challenges and opportunities that companies face in using big data to enhance green performance, and proposes corresponding strategies and suggestions. Through this research, it is hoped to provide useful references for companies to achieve green transformation and sustainable development in the context of big data.

The Big Data Comprehensive pilot Zone takes innovation as the main line to promote digital and green industry development. It helps companies to channel more resources into the big data-related industry, unleashing strong development momentum of data elements, playing an important role in establishing a sound economic system for green, low-carbon and sustainable development. Therefore, the innovations and marginal contributions of this article include the following three aspects: Firstly, for the first time, green performance is included as the explained variable in the testing mechanism of the Big Data Comprehensive pilot Zone. Existing research mainly focuses on the impacts of technological innovation and digital transformation brought by the Big Data Comprehensive pilot Zone. However, research on the impact of green performance seems relatively scarce.

Based on the above background, this study chooses the Big Data Comprehensive pilot Zone as the starting point of analysis to examine in detail how this pilot zone specifically influences green performance and reveal the underlying mechanisms. Secondly, the study comprehensively explores the heterogeneous effects of the Big Data Comprehensive pilot Zone on the development of green performance from the perspectives of enterprise attributes, industry attributes, and regional attributes. In order to address important endogeneity issues, this paper designs a double difference analysis framework aiming to more accurately measure and evaluate the actual effects of the establishment of the Big Data Comprehensive pilot Zone on policy influences.

II. Theory and Hypothesis

II. A. The impact of big data integrated pilot zone on the green performance of enterprises

The key tasks of the Big Data Comprehensive pilot Zone include the following four aspects: first, focusing on in-depth exploration of policy and system optimization, institutional innovation, and service mode innovation, improving the legal and regulatory system of big data and embracing prudent regulation of new formats, to create a source of institutional innovation for big data and build a leading area for institutional innovation. The second is to establish a leading area for the development of the big data industry, achieving a twofold increase in the value added of the digital economy. Third, to focus on improving the digital social governance system and digital livelihood service system, forming application scenario clusters in areas such as government services, rural revitalization, ecological civilization, urban management, livelihood security, and life services, creating benchmarks for precision and intelligence in social governance and equalization and universalization in livelihood services. Fourth, to explore the establishment of a cross-regional data circulation and collaborative computing mechanism, promote the formation of a new national pattern of "East data, West computing," and build a strategic hub for national computing power network.

First of all, as a government-promoted innovative practice platform, the Big Data Integrated pilot Zone has gathered a large amount of data resources [1], technology resources [2], and talent resources [3]. These resources provide the foundational conditions for companies to optimize operations and enhance competitiveness [4]. The application of big data technology has brought disruptive changes to business operations, significantly improved resource integration capabilities, and sparked stronger innovation momentum. With the support of big data technology, companies can more precisely analyze market demand, optimize production processes, reduce operating costs [5], thereby creating favorable conditions for enhancing green performance.

Secondly, Big Data Integrated pilot Zones are usually accompanied by policy support and funding to encourage businesses to engage in green technology innovation and practices [6]. These policies and funds can guide companies to increase investment in green technology research and development [7], environmental equipment upgrades [8], and drive companies towards achieving green transformation.

From the perspective of green development, the Big Data Comprehensive pilot Zone directly promotes new technological

innovations represented by big data and cloud computing [9], helping enterprises strengthen the utilization of data resources, thereby promoting technological innovation and optimizing the cost structure of enterprises to achieve innovative development of green performance. From the perspective of financial performance of the enterprises, those located in the Big Data Comprehensive pilot Zone can, to a certain extent, alleviate financial constraints by effectively utilizing big data resources [10], making it easier to obtain financial support and further promoting the expansion of innovative research and development activities. Continuously and rapidly expanding the green performance development of enterprises. Based on the in-depth analysis above, this article tentatively proposes the following hypothesis:

H1: The Big Data Comprehensive pilot Zone can significantly enhance the green performance of enterprises.

II. B. The moderating factors of big data comprehensive pilot areas on corporate green performance

Executive tenure refers to the time that the executive team has been in office in the enterprise. This article selects the average tenure of executives, which is the average tenure of each executive within the enterprise, as a moderating variable, reflecting the familiarity of the executive team with the enterprise, strategic stability, and internal cooperation level. Due to differences in the growth background, personality traits, and personal abilities of executives, they may make different decisions on the enterprise's development strategy, thereby affecting enterprise performance [11].

Firstly, reducing the average executive tenure may bring about more flexible and innovative strategic decisions. New executive members may be more inclined to adopt new technologies and methods [12], including the application of big data technology in enterprise operations, to drive the enterprise's green transformation. This helps the enterprise better utilize data resources in the big data comprehensive test area to enhance green performance.

Secondly, the average tenure of top executives can comprehensively reflect their management thinking, maturity, experience accumulation, and sense of responsibility [13]. Hambrick and Fukutomi pointed out in their 1991 study [14] that companies with longer average tenure of top management teams tend to be less sensitive to changes in internal and external environments, easily falling into a fixed mindset. This leads to a certain path dependence in managing the company, indirectly resulting in a gradual decrease in innovation input. Research by Grimm and Smith (1991) [15] found that as the average tenure of executives increases, they are more likely to fall into a contented and conservative mindset, making them appear less firm in their willingness and confidence to drive strategic changes in the company. As Barker and Mueller (2002) [16] pointed out, despite maintaining a conservative and limited attitude towards investment in new product and technology research and development, it is actually through increasing research and development investment that companies can inject new vitality into strategic innovation. Conversely, research by Wu et al. (2005) [17] found that companies with shorter average tenure of executives tend to increase their investment in research and development resources to drive innovation and development, as they are eager to achieve significant performance and results in a shorter period of time.

Finally, senior management itself has a certain degree of flexibility. Reasonable staff mobility not only helps in the broad dissemination of knowledge, deep communication, and efficient sharing but also promotes the adjustment of the original management approach through the spillover effect of knowledge, stimulating the vigorous development of innovative activities [18]. The preference of the management for executive compensation and the dual-innovation strategy may not be continuously strengthened with their length of tenure. In fact, as the term gradually lengthens, especially when encountering cognitive bottlenecks or challenges in their career, the management is more likely to prefer maintaining the current status [19]. In this context, if innovation attempts fail, the accumulated social reputation and market value of managers may be damaged. Therefore, they may adopt a "risk-averse, status quo maintenance" strategy, which often leads them to be conservative in decision-making, holding a resistant attitude towards any form of change and innovation activities. Based on this, this paper proposes the hypothesis:

H2a: Reducing the average tenure of top executives can effectively promote the relationship between big data pilot zones and companies' green performance.

Adjusting the credit term structure as an economic measure not only impacts the financial sector but may also have far-reaching effects on industrial structure and corporate operational strategies. The direct benefits for companies include various policy supports such as tax incentives, direct financial subsidies, and expanded bank loans [20]. Shortening the credit term structure implies that companies need to repay loans in a shorter period, increasing liquidity pressure but potentially prompting a focus on fund efficiency and risk management. Amid the backdrop of big data pilot zones, this pressure could drive companies to utilize big data technology for refined operations and decision-making, enhancing resource utilization efficiency, reducing unnecessary waste, promoting green technology innovation, and mitigating financial risks and financing pressures associated with technological innovation.

Secondly, the policies in the big data comprehensive pilot zone utilize capital and financing channels to control the scale of corporate debt financing [21], shorten credit terms to enhance the innovation capabilities and green performance of enterprises [22], accelerate corporate transformation [23] and upgrading, and generate certain innovative compensation effects [24]. Furthermore, some project funding support brought about by the policies can stimulate the intrinsic motivation of enterprises for green technological innovation, thus improving environmental performance, as well as financial

performance indicators such as ROA and ROE [25]. In other words, the policies in the big data comprehensive pilot zone have a positive impact on the sustainable development and green performance of enterprises.

Lastly, big data pilot zones typically gather a large number of innovative enterprises and research institutions. These entities, through the application of big data technology, can more accurately grasp market demand, optimize production processes, and reduce operating costs [26]. The restructuring of credit term length may further stimulate these enterprises to increase their investment in big data technology, thereby accelerating technological innovation and industrial upgrading. As for corporate green performance, it encompasses various aspects of a company's performance in ecological environmental protection, resource utilization, and social responsibility. The restructuring of credit term length may indirectly impact a company's green performance by influencing its operational strategy and investment decisions. For example, companies facing greater financial pressure may be more inclined to choose green and sustainable production methods to reduce costs and enhance their brand image. Based on this, this study puts forward the hypothesis:

H2b: Shortening the credit term structure can effectively promote the relationship between big data pilot zones and green performance of enterprises.

In the current era of big data, companies must possess a matching digital foundation and environment. The company's own level of digital development will also impact the development process of the big data comprehensive pilot zone [27]. Companies with a high level of digitalization will more actively enhance digital innovation technology, improve the digital environment through supportive policies, and carry out adaptive reforms and innovations [28]. For companies with a high level of digital development, they can better utilize the big data comprehensive pilot zone to participate in cross-border multi-party ecological co-construction, value co-creation, and win-win cooperation, thereby accelerating technological updates and enhancing innovation capabilities.

Firstly, improving the level of digital development means that companies can more effectively utilize big data and other digital technologies [29], optimizing their operations and decision-making processes. In the big data pilot zone, these technologies are widely applied, providing businesses with more precise market insights, more efficient resource management, and more environmentally friendly production methods. Through data analysis, companies can better understand their business processes, identify potential areas for improvement, thus reducing costs, improving efficiency, and reducing environmental burdens.

Secondly, an elevated level of digital development contributes to driving green innovation in companies. By utilizing big data and artificial intelligence technologies, companies can develop more environmentally friendly products and production processes, reducing energy consumption and pollution emissions. Additionally, digital technologies can also help companies achieve more precise energy management and resource recovery, further reducing waste and pollution.

Lastly, within the context of the big data pilot zone, enhancing the level of digital development also promotes cooperation and knowledge sharing among companies. This helps in forming a tighter industrial chain and supply chain, driving the overall green transformation of the entire region. By sharing data, experiences, and best practices, companies can collectively address environmental challenges and achieve sustainable development. Based on this, the hypothesis proposed in this paper is:

H2c: Improving the level of digitalization plays a significant facilitating role in enhancing the relationship between the big data pilot zone and the green performance of companies.

III. Research Design

III. A. Data source

This study aims to delve deeply into the specific impact of the Big Data pilot Zone on the green performance of listed companies within the zone. Chinese A-share listed companies were selected as research samples, focusing on data from the time window between 2012 and 2022. In terms of data sources, this research comprehensively utilized the CSMAR database, Wind database, and official data from the China National Intellectual Property Administration, while also referring to the listed companies' financial annual reports and announcements.

In the data processing stage, the following measures were taken to ensure the accuracy and reliability of the data: during the initial screening process, companies labeled as special treatment (ST, *ST), those under suspension of trading or already delisted were excluded to ensure that the study is not affected by abnormal market behavior or special events, thus avoiding market fluctuations or disturbances from special circumstances on the research results. Secondly, considering the uniqueness of the financial and insurance industries, they were also excluded from the sample. Finally, to eliminate the influence of extreme values on the analysis results, we conducted a top and bottom 1% trimming of continuous indicators, ultimately retaining 2207 companies for in-depth analysis.

III. B. Variable Selection

III. B. 1) The explanatory variables: Green Performance (GP)

This paper measures corporate green performance through four categories of indicators. Firstly, corporate financial

performance is measured through the return on total assets in the WIND data. Secondly, corporate social performance is measured by referring to the research of Xue Mei Jie and Zhu Qi Wei (2021), using the scores of environmental management practices and social management practices in the ESG ratings of WIND. Thirdly, environmental performance of the company is measured through the social management practice scores in the ESG ratings of WIND. Fourthly, green innovation performance is measured by the number of green patents published by the company. By using the entropy weight method to combine the four indicators, a proxy indicator representing green performance can be obtained. When using a multi-indicator system to conduct a comprehensive evaluation of a specific object, as the number of indicators increases, there will be a certain degree of overlap in the information between the indicators, necessitating their reconsideration and integration. The entropy weight method can better preserve the original information, thus this paper selects the entropy weight method to construct a comprehensive indicator of corporate green performance.

III. B. 2) Core explanatory variable: policy variables of integrated big data pilot zones ($Treat_i \times Policy_{it}$)

The policy variable for the Big Data Comprehensive pilot Zone is a combined dummy variable, with a value of 1 assigned to enterprises located within the province and city designated as part of the Big Data Comprehensive pilot Zone, and 0 otherwise. In our study, we set the specific policy implementation time points as 2015 and 2016. Specifically, for enterprises in the pilot area of the Big Data Comprehensive pilot Zone in Guizhou Province, their policy implementation time is marked as 2015; while for other enterprises located within the pilot Zone but not part of the pilot project in Guizhou Province, the policy implementation time is set as 2016. To quantify this policy impact, we establish a policy variable: for those enterprises located in specific pilot areas and affected by the policy from the year of its implementation onwards, we set the corresponding policy indicator to 1. If an enterprise is not within these areas or beyond their scope of influence, the indicator is set to 0. Through regression analysis of the policy variables in the Big Data Comprehensive pilot Zone, we can elucidate the extent and trend of the policy's impact on the green performance of enterprises.

III. B. 3) Control variables

To improve the estimation accuracy of the double difference model and to evaluate more precisely the impact effect of the Big Data Integrated pilot Zone on the green performance of enterprises, this study also considers various other potential influencing factors (Table 1). In terms of corporate characteristics, enterprise age and enterprise size are selected as control variables, where the age of existence (Age) is represented by the logarithm of the year of establishment, and enterprise size (Size) is characterized by the logarithm of total assets at the end of the year; in terms of the financial characteristics of the enterprise, the asset-liability ratio is measured as the proportion of total liabilities to total assets, profitability is measured as the ratio of net profit to total assets, and the revenue growth rate is measured as the ratio of revenue growth to initial revenue. The digital level of enterprises to some extent reflects the degree to which enterprises are influenced by the Big Data Integrated pilot Zone. This study crawled annual reports of 2,207 listed companies and measured the proportion of the number of words related to digitalization, big data, and digital transformation in annual reports to the total number of words. Intangible assets are represented by the share of intangible assets in the enterprise; in terms of the corporate governance structure, the degree of equity concentration is quantified by the proportion of shares held by the top ten shareholders.

III. C. Modeling

III. C. 1) The baseline model

In order to more accurately explore the impact of the comprehensive pilot zone of big data on the development of green performance of enterprises, taking into account that the traditional double-difference method can not meet the policy impacts at multiple time points, a multi-period double-difference model is constructed as follows.

$$GP_{it} = \alpha + Treat_i \times Policy_{it} + \gamma X_{it} + YearFE + FirmFE + \varepsilon_{it} \quad (1)$$

In this paper, enterprises in the comprehensive big data pilot zone are grouped according to their geographic location. Specifically, the grouping variable is set as a binary variable, and for enterprises located in the pilot area, if they are established in the year of policy implementation or after, the policy variable is set to 1; otherwise, it is set to 0. In addition, this paper also sets a time grouping variable, which is assigned a value of 1 when the enterprise is in the year of the implementation of the policy of the national big data comprehensive pilot area and the year after, and 0 in the previous year.

In order to deeply investigate the impact of the big data synthesizer on firms' green performance, this paper introduces a core explanatory variable, namely the interaction term between the firm grouping and the time grouping $Treat_i \times Policy_{it}$. This variable can help us capture more accurately the dynamic relationship between big data pilot zone policies and firms' green performance.

Table 1: Statistics of variables

variables	Definition
The dependent variable	
Green Performance (GP)	Financial performance (FP): the return on assets of the enterprise
	Social Performance (SP): the corporate social management practices score on the ESG scale
	Environmental Performance (EP): the ESG score for a company's environmental management practices
	Green Innovation Performance (GI): number of patent applications filed by firms
	Green Performance (GP): entropy weights of the above four indicators
The independent variable	
Policy variables ($Treat_i \times Policy_{it}$)	($Treat_i \times Policy_{it}$) is the interaction term between the firm grouping and the time grouping, which takes the value of 1 for the pilot group and 0 for the control group.
control variables	
Age of business	Year of establishment of the enterprise
Enterprise Size	total assets of the enterprise
Gearing ratio (Lev)	total liabilities/total assets
Profitability (PR)	net profit/total assets
Growth in operating income (Growth)	Increase in operating income/opening operating income
Level of digitization (DT)	The number of digitization-related terms in corporate annual reports as a proportion of the total number of words in the full text
Share of intangible assets (Ias)	intangible assets/total assets
Shareholding Concentration (SC)	Shareholding of top ten shareholders

In addition, this paper considers a series of control variables that may affect the development of firms' green performance in order to more comprehensively assess the effects of the Big Data Comprehensive Pilot Zone policy. Meanwhile, year fixed effects are introduced in order to eliminate the unpredictable and heterogeneous disturbances YearFE and firm-individual fixed effectsFirmFE, to ensure the robustness and reliability of the findings.

III. C. 2) Parallel trend test

A central prerequisite in applying the double-difference (DID) analytical framework is to ensure the existence of so-called parallel trends. This means that the pilot and control groups in the study should have demonstrated consistent trajectories on key indicators before the intervention was implemented. Only when this assumption is fulfilled can we consider the estimation results of the DID model to be reliable and free from bias. In order to test this assumption, this paper employs a specific model for the parallel trend test.

$$GP_{it}=\alpha_1+\sum \delta_k[Treat_i \times (t=k)]+\gamma_1 X_{it}+YearFE+FirmFE+\varepsilon_{it} \quad (2)$$

In this paper, we set parameter k to denote the kth year after the launch of the comprehensive pilot zone for big data or the corresponding year before the launch. In order to enhance the reliability of the model predictions and to prevent the interference of multicollinearity, we select the year before the implementation of the policy as the reference year, based on which the parallel trend is verified.

III. C. 3) Moderating effects

The purpose of this study is to explore in depth how the establishment of the comprehensive pilot zone for big data intrinsically affects the green performance of enterprises. To this end, we extend the analysis based on model (1) and construct the following extended model by introducing three moderating variables, namely, the average tenure of senior executives, the structure of credit term, and the level of digital development of enterprises. These variables will help us to understand more deeply how the policies of pilot zones affect the green performance of enterprises through these factors.

$$GP_i=\alpha_1+\beta_2 Treat_i \times Policy_{it}+\mu Treat_i \times Policy_{it} \times Med_i+\gamma_2 X_{it}+YearFE+FirmFE+\varepsilon_{it} \quad (3)$$

Within the framework constructed in this study, this paper incorporates a series of control factors and sets μ to represent the regression results of the interaction between policy parameters and these control factors. When μ shows significance in statistical significance, it indicates that the establishment of the comprehensive pilot zone of big data has promoted the improvement of green performance of enterprises.

IV. Empirical study

IV. A. Descriptive statistics

Table 2 lists the descriptive statistics of each variable in detail, covering key statistical indicators such as the mean, variance, minimum and maximum values of the variables. From the table, we can clearly observe that: the mean value of green performance is 0.019, the minimum value is 0.001, the maximum value is 0.122, the distance between the maximum value and the mean value is larger, and exceeds the range of the variance, indicating that the green performance of the enterprises has a large difference; the mean value of the DID is 0.233, the minimum value is 0, and the maximum value is 1, which shows that the data are in a relatively reasonable and controllable range. The mean value of DID is 0.233, the minimum value is 0, and the maximum value is 1. This value shows that the data are within a relatively reasonable and controllable range. Further analysis shows that the standard deviation of most variables is smaller than their mean values, which indicates that the sample data fluctuate less, and the data are relatively stable and reliable.

Table 2: Descriptive statistics

	N	Mean	SD	Min	Max
GP	23337	.019	.015	.001	.122
did	23337	.233	.423	0	1
Age	23337	20.494	6.272	2	68
size	23337	8.49	1.338	4.062	14.791
Lev	23337	41.998	19.672	.797	103.726
PR	23337	4.452	7.084	-80.487	118.186
Growth	23337	14.743	85.927	-130.916	8748.366
Ias	23337	4.937	6.303	0	85.21
SC	23337	54.799	18.376	0	101.16

IV. B. Benchmark regression

In further baseline regression analysis, as can be seen in column (1) of Table 3, after controlling only for individual fixed effects and time fixed effects, the Big Data Integrated Pilot Zone has a significant positive impact on the green performance of enterprises, and this impact is obvious at the 1% significance level. Subsequently, in column (2), this paper adds control variables such as enterprise age and size, but this positive effect is still significant, which again verifies the positive promotion effect of big data comprehensive pilot zone on enterprise green performance. This result strongly supports hypothesis H1, that is, the comprehensive pilot zone of big data can significantly drive the development of green performance of enterprises.

In order to further eliminate the interference of other potential factors on green performance, we further control for the firms' own characteristics, financial characteristics and differences in governance structure in column (2). By controlling in this way, we expect to be able to more accurately assess the impact of the Big Data Comprehensive Pilot Zone on firms' green performance.

From the regression results of the control variables, the coefficients of the two variables, enterprise size and enterprise equity concentration, are significantly positive, which indicates that a larger enterprise size and a relatively concentrated equity will be conducive to the enterprise's green technological innovation and the development of green performance. In addition, the coefficient of the gearing ratio variable is negative but not significant, which indicates that the increase in the size of corporate debt cannot play a role in enhancing green performance. The reason for this may be that enterprises are unable to flow profits into green innovation and digital transformation investment due to the increase of debt, which will indirectly lead to the slow incentive effect of the big data comprehensive pilot zone policy.

IV. C. Parallel trend tests

The first and crucial step in the analysis using the double difference model (DID) is to conduct a parallel trend test. The purpose of this step is to verify whether enterprises in the Big Data Comprehensive Pilot Area (i.e., the pilot area) and those in the non-pilot area show a similar pattern, i.e., there is no significant difference in the trend of digital transformation before the policy is formally implemented. Such a test is an important basis for ensuring the validity of the results of the DID model analysis. To test this hypothesis, this paper adopts an event study approach. Specifically, we created dummy variables representing the four years before and after the implementation of the policy based on the time intervals of the sample, and generated interaction terms with the dummy variables of the treatment group (i.e., enterprises located in the Big Data Comprehensive Pilot Zone). These interactions were selected as explanatory variables in regression analyses aimed at elucidating the differences in environmental performance between firms in the pilot group and those in the non-pilot group (i.e., control firms) in a given year.

Table 3: Benchmark regression

	(1)	(2)
variables	Benchmark regression	Benchmark regression
did	0.00229***	0.00173***
	(4.006)	(3.281)
Age		-0.00817**
		(-2.103)
size		0.00505***
		(16.240)
Lev		-0.00001
		(-0.975)
PR		-0.00015***
		(-10.441)
Growth		-0.00000***
		(-3.645)
Ias		-0.00005
		(-1.497)
SC		0.00003***
		(4.148)
Observations	23,336	23,336
R-squared	0.596	0.617

Robust t-statistics in parentheses*** p<0.01, ** p<0.05, * p<0.1

Figure 1 shows the results of the parallel trend validation on green performance. According to this figure, we observe that the coefficients of the interaction term (pre) are not significant in the years before the official implementation of the policy, which implies that there is no significant difference in the development trend of green performance between firms in the pilot area and firms in the non-pilot area before the effect of the policy is realized. This is in line with the parallel trend hypothesis, that is, the two groups of firms should have similar patterns of change before the policy intervention. However, once the policy was implemented, the coefficient of the interaction term (post) started to become significant after the policy was implemented. This change suggests that policy implementation has a significant effect on the green performance of firms in the pilot area, and that this effect is gradually visible in the years after policy implementation. This further proves that the model satisfies the parallel trend hypothesis and that the impact of policy implementation on green performance has a certain time lag effect.

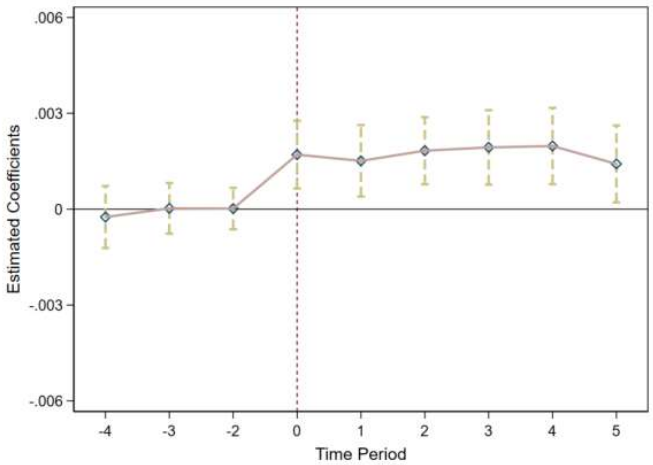

Figure 1: Parallel trend test

IV. D. Placebo test

In order to more precisely assess the impact of the Big Data Comprehensive Pilot Zone policy on firms' green performance, this paper controls for a number of factors that may affect the development of green performance in the baseline model. Subsequently, in order to exclude the interference of other potential factors on the assessment of policy effects, we further implemented a placebo test. The test was operationalized as follows: first, we randomly selected the same number of cities as the number of comprehensive big data pilot zones and constructed dummy pilot policy variables based on these cities. Then, we set 2015 and 2016 as the hypothetical policy implementation years, and randomly selected pilot group enterprises, and constructed the corresponding dummy pilot group variables at the same time. After conducting 500 simulations, we generated a kernel density distribution plot based on the estimated coefficients of the pseudo-policy dummy variables, which is specifically displayed in Figure 2. This figure clearly depicts the results of the random sample regression analysis of green performance. As can be seen in Figure 2, the coefficients from the random sample regression are mainly clustered around the zero value, which is significantly different from the regression coefficients after the implementation of the policy in the real situation. In addition, further analysis shows that most of the p-values exceed the significance threshold of 0.1, which clearly indicates that the effects of the randomly selected simulated policy factors on the environmental performance of firms are not significant. This result validates the randomness we used in the simulation, and this result strongly proves that the findings of this paper are not interfered by other random factors, thus further confirming the robustness of the findings.

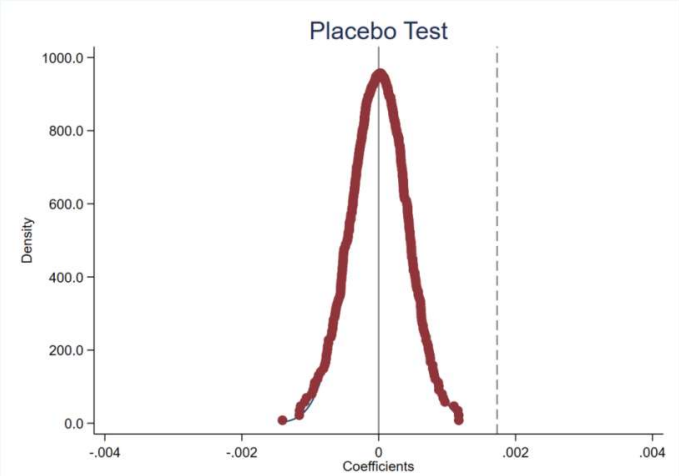

Figure 2: Placebo test

IV. E. Other robustness tests

IV. E. 1) Replacement of explanatory variables

In order to eliminate the interference of confounding factors in the previous analysis, this paper reconsiders and redraws the indicators for measuring the green performance of enterprises. In view of the limitations of the number of invention patent applications in comprehensively depicting the enterprises' digital transformation inputs, we decided to adopt the total innovation inputs of enterprises as a proxy variable to more comprehensively reflect the enterprises' innovation activities and green performance. Subsequently, we again utilized the entropy weighting method to calculate the comprehensive score of green performance to ensure the accuracy and reliability of the assessment results.

Through regression analysis, we get new results as shown in Table 4. Further observing columns (1) and (2) in Table 5, it can be clearly seen that the regression coefficients of the policy variables are still positive at 1% significance level after replacing the explanatory variables with the total amount of firms' innovation inputs, and this result is consistent with the previous one, thus verifying the relative robustness of our research methodology and conclusions.

IV. E. 2) Single-period DID

Guizhou Province was established as a comprehensive pilot zone for big data in 2015, and all other pilot comprehensive pilot zones for big data were established in 2016. Referring to the research method already developed, excluding the sample of Guizhou province's comprehensive pilot zone of big data that was established separately in 2015, and unifying 2016 as the starting point of the official implementation of the policy, we reevaluated the implementation effect of the policy. The data in column (2) of Table 4 show that the regression results remain significantly positive at the 1% level after changing the multi-period double-difference method to the single-period double-difference method.

IV. E. 3) To the exclusion of other policies

Within the time frame of this study, firms' innovative behaviors may be affected by the complex interaction of multiple policy factors, which may cause systematic errors in the results of the benchmark regression analysis. Therefore, in order to accurately measure the actual impact of the establishment of the comprehensive pilot zone for big data on firms' innovation activities, a more detailed analysis is needed. In this paper, the relevant policies launched by the government around 2015 are scrutinized in depth, and the pilot policy of carbon emissions trading and the green financial reform and innovation policy are selected as the focus of further research. By introducing the dummy variables of these two policies into the model, we are able to more comprehensively analyze their impact on corporate innovation activities.

In the regression analysis, we include the dummy variables for the carbon emissions trading pilot policy and the green financial reform and innovation policy, respectively, as well as the dummy variables for both policies in the model. The results are shown in columns (4) and (5) of Table 4, which show that although the promotion effect of the establishment of the comprehensive big data pilot zone on firms' environmental performance is weakened after taking these additional policy factors into account, it still maintains a positive and significant effect. This result implies that the previous assessment of the policy effects of the Big Data Comprehensive Pilot Zone may have been slightly optimistic, however, it cannot be ignored that the establishment of the Pilot Zone does effectively enhance the green performance of firms.

Table 4: Stability tests

	(1)	(2)	(3)	(4)	(5)
variables	Replacing the explanatory variables	Single-period DID	Excluding carbon trading pilot policies	Excluding green financial reform and innovation policies	Excluding both of these policies at the same time
did	0.00348***	0.00168***	0.00129**	0.00171***	0.00130**
	(4.349)	(3.159)	(2.442)	(3.186)	(2.426)
Age	-0.00894**	-0.00818**	-0.00685***		-0.00687***
	(-2.225)	(-2.107)	(-4.295)		(-4.292)
size	0.00835***	0.00505***	-0.00852**	-0.00815**	-0.00852**
	(17.013)	(16.243)	(-2.198)	(-2.101)	(-2.199)
Lev	-0.00006***	-0.00001	0.00506***	0.00504***	0.00506***
	(-3.890)	(-0.973)	(16.410)	(16.218)	(16.409)
PR	-0.00011***	-0.00015***	-0.00001	-0.00001	-0.00001
	(-7.136)	(-10.452)	(-0.972)	(-0.980)	(-0.970)
Growth	-0.00000***	-0.00000***	-0.00015***	-0.00015***	-0.00015***
	(-3.873)	(-3.646)	(-10.501)	(-10.430)	(-10.500)
Ias	-0.00002	-0.00005	-0.00000***	-0.00000***	-0.00000***
	(-0.604)	(-1.496)	(-3.693)	(-3.635)	(-3.699)
SC	0.00001	0.00003***	-0.00005	-0.00005	-0.00005
	(0.727)	(4.140)	(-1.590)	(-1.483)	(-1.595)
			0.00003***	0.00003***	0.00003***
Observations	23,336	23,336	(4.039)	(4.149)	(4.039)
R-squared	0.743	0.617		0.00020	-0.00006

Robust t-statistics in parentheses*** p<0.01, ** p<0.05, * p<0.1

IV. F. Heterogeneity analysis

In a preliminary benchmark regression analysis, after a comprehensive study, we confirm that the Big Data Comprehensive Pilot Zone (BDCPZ) has had a significant catalytic effect on innovative activities across a broad sample of firms. Nevertheless, due to the heterogeneity of the sample population, some specific differences and details may not be fully revealed. In view of this, we will conduct a more detailed and in-depth analysis with a view to obtaining a more accurate understanding of this facilitation mechanism.

IV. F. 1) Firm heterogeneity

Given the diversity of firms' ownership structures, these firms exhibit marked differences in terms of institutional advantages, resource allocation and access to external finance. This diversity leads to different responses in environmental performance when enterprises are affected by innovation policies such as the Big Data Comprehensive Pilot Zone Policy. In order to analyze this phenomenon in depth, this study divides enterprises into two categories, state-owned and non-state-owned, based on the nature of their ownership, and explores the differences in the impacts of the Big Data Comprehensive Pilot Zone policy on the environmental performance of these two types of enterprises.

According to the data in table 5, columns 1 and 2 show that SOEs are affected by the policy dummy variable, the estimated coefficient of which is positive, but this effect does not show statistical significance. This may be due to the fact that SOEs usually have a more stable business environment and resource security, which makes them relatively less sensitive to external policy changes. In addition, SOEs may be more influenced by the government's administrative directives and programmatic

guidance, and their business decisions and resource allocation may not be entirely based on market principles, which may also weaken the promotion effect of the Big Data Comprehensive Pilot Zone policy on their green performance to a certain extent. State-owned enterprises (SOEs) need to coordinate with various departments and consider other constraints such as costs, and the implementation of some policies lacks real-time performance. In addition, the resource endowment of SOEs is more advantageous than that of other enterprises, but due to the lack of obvious motivation for transformation of some enterprises and the influence of a variety of comprehensive factors, the effect of the comprehensive pilot zone of big data on enterprise empowerment is not significant enough.

Nonetheless, NSOEs show different dynamics in facing this problem. By analyzing the estimation results of the policy dummy variables, we find that the coefficients are positive at the 1% significance level, which clearly indicates that the policy pilots in the Big Data Comprehensive Pilot Zone significantly contribute to the green performance improvement of NSEs. This result highlights the important role of the big data comprehensive pilot zone policy in promoting the green transformation and performance improvement of NSOEs. As NSEs face greater competition for resources and technology, the incentive effect of the policy can alleviate a series of problems such as resource constraints, financing and technological innovation, and therefore NSEs have a strong willingness to undergo digital transformation, and the effect of the policy in the comprehensive big data pilot zone is more obvious.

IV. F. 2) Regional heterogeneity

Due to the different characteristics of the pilot regions of the policy of the comprehensive pilot zone of big data, there are significant differences in the level of innovation, financing constraints and scientific and technological resources of enterprises, and these differences will have an important impact on the development and operation of enterprises, resulting in enterprises showing different adaptive capacity and reaction speed in the face of market changes, competitive pressures and external environments. Accordingly, based on the characteristics of the region, the provinces where the enterprises are located are divided into innovative and non-innovative provinces. In order to explore the differences in the impacts of the Big Data Comprehensive Pilot Zone policy on the green performance under the nature of the different regions, an in-depth analysis is carried out. In the data in columns (3) and (4) of Table 5, for those provinces with innovation as the core feature, although the predictive coefficients of the policy dummy variables show a positive trend, this trend is not statistically significant. The reason behind this phenomenon may be that these innovative provinces already have a high level of green performance and innovation potential, and the effect of the Big Data Comprehensive Pilot Zone policy in these areas may be relatively limited, making it difficult to generate significant additional impetus. The policy advantages of the big data pilot zones are not easily demonstrated by the high endowment of scientific and technological resources, advanced industrial structure and significant regional economies of scale in the industry in the innovation-oriented provinces.

For non-innovative provinces and regions, the analysis of the policy dummy variables shows a significant positive impact, a finding that strongly suggests that the policy of the comprehensive big data pilot zone has played a positive role in promoting the green performance of enterprises. The study shows that the policy pilot of the comprehensive big data pilot zone significantly contributes to the improvement of environmental performance of NIEs, and this effect is significant. This may be due to the existence of enterprises with higher financing constraints in non-innovative provinces, which can use more funds to carry out technological innovation, and the more significant effect of industrial regional economies of scale, which is easy to have a positive linkage with the development of green innovation and green performance.

IV. F. 3) Industry heterogeneity

In terms of the industries in which the enterprises are located, enterprises in high-tech industries that prioritize the development of high-tech industries have a certain first-mover advantage and are more likely to cooperate with the implementation of the policy of the comprehensive pilot zone of big data. Based on the differences between industries, we conducted a group test to further investigate. According to the results presented in columns 5 and 6 in Table 5, we find that for non-high-tech industries, although the impact of the comprehensive pilot zone of big data on green performance is not significant, it still produces a certain positive impact, which may be attributed to the following reasons: in non-high-tech industries, due to the relative lag in technological updating and the insufficiency of talent reserves, human capital and technological capital introduced by the policy of comprehensive pilot zone of big data are often difficult to be fully and effectively utilized, and the human capital and technological capital introduced by the policy of comprehensive pilot zone of big data are often difficult to be fully and effectively utilized. technology capital introduced by the comprehensive pilot zone policy are often difficult to be fully and efficiently utilized. To some extent, this has limited the ability of these industries to maximize the benefits of the policy, and the technology, talent and capital needed for green performance development have not been met.

The implementation of the pilot policy of the Comprehensive Big Data Pilot Zone has significantly boosted the green performance of enterprises. This is mainly due to the strong innovative capacity and resource advantages of high-tech industries. When these industries are combined with the policy advantages of the Big Data Comprehensive Pilot Zone, they can more effectively promote the green performance of enterprises. Therefore, compared with other industries, enterprises in

the high-tech industry show a stronger positive response when they are affected by the pilot policy of the Big Data Comprehensive Pilot Zone.

For high-tech industries, the estimated coefficients of the policy dummy variables are significantly positive at the 1% level, which is mainly attributed to the strong innovation ability and resource advantages of high-tech industries. This is mainly attributed to the strong innovation ability and resource advantages of high-tech industries. When these industries are combined with the policy advantages of the Big Data Comprehensive Pilot Zone, they can more effectively promote the green performance of enterprises. Therefore, compared with other industries, enterprises in the high-tech industry show a stronger positive response when they are affected by the pilot policy of the big data comprehensive pilot zone.

Table 5: Heterogeneity test

	(1)	(2)	(3)	(4)	(5)	(6)
variables	State-owned enterprises	Non-State-owned Enterprises	Innovative provinces	Non-innovative provinces	High-tech industries	non-high-tech industries
did	0.00079	0.00253***	0.00100	0.00409***	0.00189***	0.00105
	(0.842)	(4.373)	(1.577)	(4.117)	(3.418)	(0.860)
Age	-0.00576	-0.00971**	-0.00777*	-0.01257	-0.00593	-0.01322**
	(-0.777)	(-2.153)	(-1.909)	(-1.231)	(-1.259)	(-2.518)
size	0.00537***	0.00409***	0.00479***	0.00549***	0.00462***	0.00588***
	(8.707)	(11.852)	(13.478)	(8.926)	(13.981)	(7.662)
Lev	-0.00002	-0.00002	-0.00001	-0.00001	0.00000	-0.00008***
	(-1.007)	(-1.342)	(-1.062)	(-0.231)	(0.101)	(-2.747)
PR	-0.00022***	-0.00010***	-0.00014***	-0.00020***	-0.00014***	-0.00018***
	(-6.178)	(-6.526)	(-8.559)	(-5.812)	(-8.936)	(-4.518)
Growth	-0.00001**	-0.00000***	-0.00000***	-0.00001	-0.00000***	-0.00000
	(-2.377)	(-2.898)	(-3.460)	(-1.515)	(-3.477)	(-0.735)
Ias	-0.00010*	0.00002	-0.00002	-0.00010*	-0.00004	-0.00008
	(-1.734)	(0.559)	(-0.579)	(-1.667)	(-1.320)	(-0.900)
SC	0.00004**	0.00004***	0.00004***	0.00001	0.00002*	0.00008***
	(2.501)	(4.872)	(4.712)	(0.525)	(1.764)	(6.007)
Observations	9,407	13,929	16,678	6,658	16,684	6,652
R-squared	0.610	0.608	0.625	0.601	0.625	0.606

Robust t-statistics in parentheses*** p<0.01, ** p<0.05, * p<0.1

IV. G. Moderating effects

In order to test the previous speculation, we conduct further analysis. By interacting the average tenure of the firm's senior management (Executives), the firm's credit maturity structure (Maturity), and the degree of digitization (Digitization) with the policy dummy variables, this study aims to explore whether these variables may influence the policy effect of the aim is to investigate whether these variables may affect the moderating effect of policy effects. In order to study whether the effect and continuity of policy implementation are affected by the tenure of executives, the average tenure of executives of enterprises is selected for quantitative analysis; in order to quantify the financing leverage of enterprises, the ratio of long-term loans to short-term borrowings of enterprises is selected for quantitative analysis; the level of digitization of enterprises is measured by crawling the keyword frequency of some conceptual keywords of datatization and big data in the enterprise's annual report through Python, the higher frequency of such keywords means the higher level of digitization of enterprises, the higher frequency of such keywords means the higher level of digitization of enterprises. The higher frequency of such keywords means the higher level of enterprise digitization.

In column (1) of Table 6, we test the moderating effect of the average tenure of corporate executives. The results show that the coefficient of the cross-multiplier term is significantly negative at the 1% confidence level, which verifies hypothesis H2a. This finding suggests that the establishment of a big data integrated pilot zone has a more significant effect on firms' green performance when the average tenure of executives is shorter. This finding suggests that the establishment of big data pilot zones has a more significant impact on firms' green performance when the average tenure of executives is shorter.

Column (2) of table 6 illustrates the moderating effect of firms' credit maturity structure. The coefficient on the cross-multiplier term is significantly negative, confirming hypothesis H2b, which suggests that when firms have relatively fewer long-term loans, i.e., when the pressure on firms to raise funds for repayment is low, they have stronger incentives to innovate and develop. Such a financial structure provides more space for enterprises to invest in green innovation and R&D,

thus generating more intellectual innovations and promoting the development of green performance of enterprises.

In column (3) of Table 6, we explore the moderating effect of digitization level. The results show that the coefficient of the cross-multiplier term is significantly positive, which confirms the hypothesis H2c, suggesting that the level of digitization can positively regulate the green performance of enterprises promoted by the establishment of the comprehensive pilot zone of big data. In other words, with the improvement of enterprise digitization level, enterprises can have more sufficient resources to invest in innovation, and these innovations further promote the development of enterprise green performance.

Table 6: Moderating effects

	(1)	(2)	(3)
variables	Average tenure of executives	credit maturity structure	Level of digitization
did	0.00211***	0.00171***	0.00169***
	(4.132)	(3.247)	(3.192)
Executives	0.00010***		
	(12.983)		
c_didc_Executives	-0.00011***		
	(-7.175)		
Age	-0.00844**	-0.00818**	-0.00819**
	(-2.120)	(-2.106)	(-2.113)
size	0.00466***	0.00504***	0.00505***
	(15.458)	(16.229)	(16.274)
Lev	-0.00001	-0.00001	-0.00001
	(-1.185)	(-0.956)	(-1.070)
PR	-0.00013***	-0.00015***	-0.00015***
	(-9.020)	(-10.391)	(-10.397)
Growth	-0.00000***	-0.00000***	-0.00000***
	(-3.137)	(-3.651)	(-3.598)
Ias	-0.00004	-0.00005	-0.00005
	(-1.155)	(-1.548)	(-1.502)
SC	0.00001	0.00003***	0.00003***
	(0.911)	(4.178)	(4.205)
Maturity		-0.00000*	
		(-1.675)	
c_didc_Maturity		-0.00002***	
		(-4.579)	
DT			-0.00002***
			(-2.767)
c_didc_DT			0.00004***
			(2.919)
Observations	23,336	23,333	23,336
R-squared	0.626	0.617	0.617

Robust t-statistics in parentheses*** p<0.01, ** p<0.05, * p<0.1

V. Conclusion

This study utilizes a dataset from 2012 to 2022, covering detailed information of 2207 listed firms in China, and employs a multi-period double-difference analysis (DID) technique in order to assess how the establishment of an integrated big data pilot zone affects the environmental performance of firms. After detailed analysis, we have come up with the following important findings: on the one hand, enterprises located in the comprehensive big data pilot zone show obvious advantages in green performance compared with enterprises in non-protest zones. On the one hand, the green performance of enterprises located in the Big Data Comprehensive Pilot Zone shows a significant advantage over non-Pilot Zone enterprises, with a 1.7% increase in green performance, and this effect shows a certain time lag. After a series of robustness tests, this conclusion is still solid. On the other hand, the moderating effect results further reveal that factors such as average tenure of executives, credit maturity structure, and digitization level of firms play key moderating roles in the promotion of green performance of firms in the Big Data Comprehensive Pilot Zone (BDCPZ). These findings suggest that the effects of different factors on policy implementation are not homogenous and fixed. More notably, government's policy-guiding behaviors have different facilitating relationships with firms' green performance in different firms and different contexts, and the form and intensity of such relationships may vary. This relationship may vary in form and intensity, and may be reflected in various aspects such as corporate governance, industry differences and geographic location.

Based on the above findings, this paper puts forward the following policy recommendations: (1) Accelerate digital transformation. Regions should enhance the level of digital development, especially those with a certain digital foundation,

should make use of the policy of comprehensive pilot zone of big data to deepen the digital reform, in order to strengthen their own digital advantages. At the same time, for different types of enterprises with different development bases, they should formulate personalized big data development strategies to fully grasp the policy opportunities.

(2) Introduce digital innovation talents. Enterprises should actively introduce digital innovation talents to improve the labor level of digital transformation and green technology innovation. Through multi-channel talent introduction programs, combined with policy guidance, enterprises are encouraged to provide better employment security to attract executives with management experience and professional background knowledge. At the same time, enterprises should improve relevant industrial support policies to meet the needs of talents in terms of living and research.

(3) Utilizing the green performance dividend. Enterprises should make full use of the promotion of green innovation and green performance in the comprehensive pilot zone of big data by combining the characteristics of the region and the industry, and formulate strategic plans in line with their own development. Enterprises in the high-tech industry should summarize their innovation experience, give full play to the advantages of innovation factor agglomeration, and promote the establishment of a new mechanism for regional coordinated development.

(4) Strengthening policy synergies. Governments and enterprises should work closely together to strengthen policy synergies. At the regional level, more efforts should be made to promote the construction of digital infrastructure to lay a solid foundation for the digital transformation of enterprises. At the enterprise level, enterprises should be encouraged to flexibly introduce various types of talents, especially professionals with overseas experience and financial background, according to their own development needs and strategic plans, so as to enhance their overall competitiveness and innovation ability. At the same time, the government should build a comprehensive and accurate human resources information database to facilitate the precise matching of jobs and realize the rational allocation and effective utilization of human resources. This not only helps enterprises to find suitable talents quickly, but also provides broader development space and opportunities for talents, thus providing strong support for the development of enterprises and talents.

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