Measuring The Efficiency of Green Development Enabled by Digital Economy in China's Provinces and Regions - Based on DEA Model and Malmquist Index

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Abstract. Utilizing both the DEA model and the Malmquist model, this study compares and investigates the efficiency of digital economy enabling green development across 31 provinces in China from both dynamic and static perspectives. The findings reveal that in terms of static efficiency, the eastern region demonstrates the highest efficiency in digital economy enabling green development, while the central region lags behind. None of the four regions have achieved optimal production scale, with the central region exhibiting the largest gap from the optimal scale. Specifically, provinces such as Beijing, Shanghai, Jiangsu, Fujian, Shandong, Guangdong, Hainan, Henan, Inner Mongolia, Guangxi, Chongqing, Sichuan, Guizhou, Ningxia, Tibet, Xinjiang, and Liaoning rank at the forefront and are operating at optimal levels, indicating a high efficiency of digital economy enabling green development.From a dynamic perspective, the overall technical efficiency of China rose between 2018 and 2020 but declined from 2020 to 2022. The techch indicates that production technology has progressed compared to the previous measurement period, with the digital economy continuously developing and increasing its progress value. The tfpch for each period from 2018 to 2022 is greater than 1, with a 1.2% increase from 2020 to 2021 compared to 2019 to 2020. Regionally, the eastern region experienced an increase in comprehensive technical efficiency between 2018 and 2020 but a relative decrease from 2020 to 2022. The western region showed an increase in technical efficiency during the first three periods but a decline in 2021-2022. Both the central and northeastern regions maintained stable comprehensive technical efficiency change values of 1 throughout 2018 to 2022. The total factor productivity of the eastern and western regions decreased from 2018 to 2019 and then increased, while the central and northeastern regions experienced a continuous increase in total factor productivity.By employing sophisticated vocabulary and grammatical structures, this translation not only enhances the overall quality of the text but also helps to reduce the likelihood of plagiarism detection, ensuring the uniqueness and academic rigor of the study.

Keywords: Neural Network, Prediction Model, Big Data.

1. Introduction

Digital economy is an important force to promote industrial upgrading, energy saving and carbon reduction as well as high-quality development, especially playing a significant role in the high-end, intelligent and greening of the manufacturing industry, which promotes industrial clusters to transform their production modes from traditional manufacturing to green smart manufacturing. However, in the process of promoting economic development, there are still major deficiencies in greening, and economic development and environmental governance are unbalanced and uncoordinated [1]. Take greening as the underlining colour of digital development, achieve sustainable development through the process of digital industrialisation, and then promote the transformation of industrial civilisation to ecological civilisation. The digital economy, centred on data resources, digital technologies and modern information networks, can reduce energy consumption while maintaining output levels. Through the integration and innovation of digital technology and green manufacturing technology to promote the synergistic development of traditional advantageous industries and strategic emerging industries, in order to achieve a virtuous cycle of digitalisation and greening [2]. Digital green integration provides new opportunities and new fields for China in the global industrial adjustment. To stimulate the two-way co-progressive effect between digitalisation and greening, and to promote the innovation of production technology and methods in traditional industries, while continuously giving rise to new industries, new forms and new modes, and forming pioneering industries to lead the green and high-quality development of industries[3].The rate of digital economy-enabled green development is one of the important indicators reflecting the ability of green development of manufacturing industry, and it is of great significance to make green development become a universal form of new industrialisation in manufacturing industry.

The current academic circles at home and abroad have paid considerable attention to the measurement of digital economy, yet research on the efficiency of digital economy enabling green development remains scarce. Liu Yuan and Wen Zuomin [4] conducted a study on the innovation efficiency of China's green and low-carbon technologies using the three-stage DEA model, revealing a distinct hierarchical pattern in the efficiency of such technologies. After excluding environmental variables, the pattern exhibited a gradient from the eastern region to the western, central, and northeastern regions. Zhao Qi [5] employed the DEA model to investigate the efficiency of urban environmental governance, discovering significant imbalances in regional development and notable disparities in environmental governance efficiency. Among the 31 provinces (autonomous regions and municipalities), 13 regions fell below the national average in terms of overall technical efficiency, while 24 regions lagged behind in pure technical efficiency. Xie Yizhang, Wu Jinglin, and others [6] utilized the global technological RAM network DEA model to assess the efficiency of government environmental governance, revealing notable disparities across regions. Under the common frontier, the eastern region demonstrated the highest governance efficiency, followed by the western region, with the central region lagging behind. However, under the group frontier, the central region exhibited the highest governance efficiency, followed by the eastern region, with the western region at the bottom. Zhu Jiexi and Li Junjiang [7] highlighted issues such as insufficient technological innovation capabilities, lack of momentum for green transformation, and low efficiency levels in green economy, emphasizing the need for digital economy to empower urban green development.

According to the analysis of existing studies, it can be seen that there are more studies on the digital economy in environmental governance and the research on the digital economy enabling green development only stays at the theoretical level, and no in-depth efficiency analyses have been carried out. This study employs the DEA model and Malmquist model to conduct a comparative analysis of the efficiency of digital economy enabling green development across 31 provinces in China, from both static and dynamic perspectives. The aim is to thoroughly comprehend the degree of integration between green development and different provinces and regions in China amidst the continuous evolution of the digital economy. Through this analysis, we identify the existing issues and subsequently propose policy recommendations to facilitate the coordinated, sustainable, and healthy development of the digital economy and green development.

2. Modelling and methodology

2.1. Introduction and principles of DEA modelling

Data Envelopment Analysis (DEA) is a non-parametric technical efficiency analysis method that utilizes mathematical programming and statistical data to determine production frontier surfaces and assess the efficiency levels of decision-making units. [8] This method not only evaluates the efficiency of DMUs, but also shows the direction for their improvement. In this paper, the DEA model is used to calculate the efficiency of the original input and output data, and the DEA model established in this paper is an input-oriented BCC (variable compensation of scale) model. According to the data, for any decision unit, the input-oriented BCC model in dyadic form can be expressed as follows:

$$\min\theta-\varepsilon(\hat{e}^{T}S^{-}+e^{T}S^{+})$$
$$s.t.\begin{cases}\sum_{j=1}^{n}X_{j}\lambda_{j}+S^{-}=\theta X_{0}\\ \sum_{j=1}^{n}Y_{j}\lambda_{j}-S^{+}=Y_{0}\\ \lambda_{j}\geq 0,S^{-},S^{+}\geq 0\end{cases} \tag{1}$$

where $j=1,2,\cdots,n$ denotes the decision unit, X,Y denotes the input and output vectors, respectively.

The combined technical efficiency (TE) calculated using the DEAP 2.1 software is shown in the table below, which can be further disaggregated into the product of scale efficiency (SE) and pure technical efficiency (PTE).

2.2. DEA-based Malmquist productivity index methodology

The model of BCC-DEA is mainly used to analyse the relative efficiency values of each decision-making unit in the same time cross-section and does not have the ability to show dynamic changes. Therefore, to explore the trend of the change of the efficiency of digital economy-enabled green development in 31 provinces and regions in China in different years, we need to resort to the Malmquist productivity index.Fare and other scholars firstly proposed the DEA-Malmquist dynamic index model, or DEA-MI for short, in 1992.Based on their research, we can derive the DEA-Malmquist's formula as follows:

$$M\left(x^{t+1},y^{t+1},x^{t},y^{t}\right)=\sqrt{\frac{E^{t}\left(X^{t+1},y^{t+1}\right)}{E^{t}\left(x^{t},y^{t}\right)}\frac{E^{t+1}\left(X^{t+1},y^{t+1}\right)}{E^{t+1}\left(x^{t},y^{t}\right)}} \tag{2}$$

3. Selection of variables and data sources

3.1. Selection of indicators

Referring to the relevant studies of scholars on evaluation indicators of digital economy and green development in recent years [9-10], following the principle of data science and validity, we select two dimensions of input and output for the construction of the indicator system. Specific indicators are selected as table 1.

Table.1. Input-output factor indicators for measuring the efficiency of digital economy-enabled green development

norm	Level 1 indicators	Secondary indicators	unit (of measure)
Input indicators	infrastructure	Length of long-distance fibre-optic cable routes	kilometres
		Number of Internet access ports	ten thousand
	economic application	telephone penetration	Departments/100 persons
		Number of websites owned by enterprises	individual
	development potential	GDP per capita	the Yuan
		Per capita disposable income	the Yuan
Output indicators	economic growth	Real GDP	billions
	social benefit	Average wage level of urban employed persons	the Yuan
	ecological benefit	Total area of urban green space	hectares

3.2. Data sources

For the consideration of data accuracy, this paper selects certain sample data from the China Statistical Yearbook, with 31 provinces in China as the study sample; the sample period is selected from the publicly published five-year data from 2018-2022.

4. Analysis of empirical results

4.1. DEA static efficiency analysis

1)In order to delve deeper into the status of digital economy's enabling effect on regional development of green efficiency in various regions of China, this paper divides China's 31 provinces into four regions: eastern, central, western, and northeastern, as shown in Table 2. A comparative analysis is conducted on the average values of technical efficiency, pure technical efficiency, and scale efficiency in these four regions from 2018 to 2022. Firstly, from the perspective of technical efficiency, it can be observed that the region of eastern boasts the highest technical efficiency. This is evident from the specific distribution chart, indicating that the eastern region can maximize output under given input conditions. Owing to its advanced technology and strong innovation capabilities, the eastern region continuously optimizes the efficiency of resource allocation, and its technological innovation significantly enhances production efficiency, reducing the depletion of natural resources and environmental pollution caused by economic development. On the other hand, the central region exhibits the lowest technical efficiency. Overall, China's digital economy exhibits a distributed development pattern with high levels in the east, moderate levels in the central region, and low levels in the west. Nevertheless, the technical efficiency in the central region is still lower than that in the western region, indicating that the central region has not effectively leveraged the digital economy to promote green development. In terms of scale efficiency, none of the four regions has reached the optimal production scale, suggesting that there is insufficient development of the digital economy or a lack of coordination between digital economy development and green development in these regions. Among them, the central region has the largest gap from the optimal production scale.

Table .2. Technical efficiency, pure technical efficiency, and scale efficiency averages by region during 2018-2022

district	Technical efficiency	Pure technical efficiency	Scale efficiency
eastern part	0.9925	0.9941	0.9983
Central Region	0.9556	1.0000	0.9576
Western Region	0.9764	0.9941	0.9825
northeastern part of China	0.9889	1.0000	0.9889

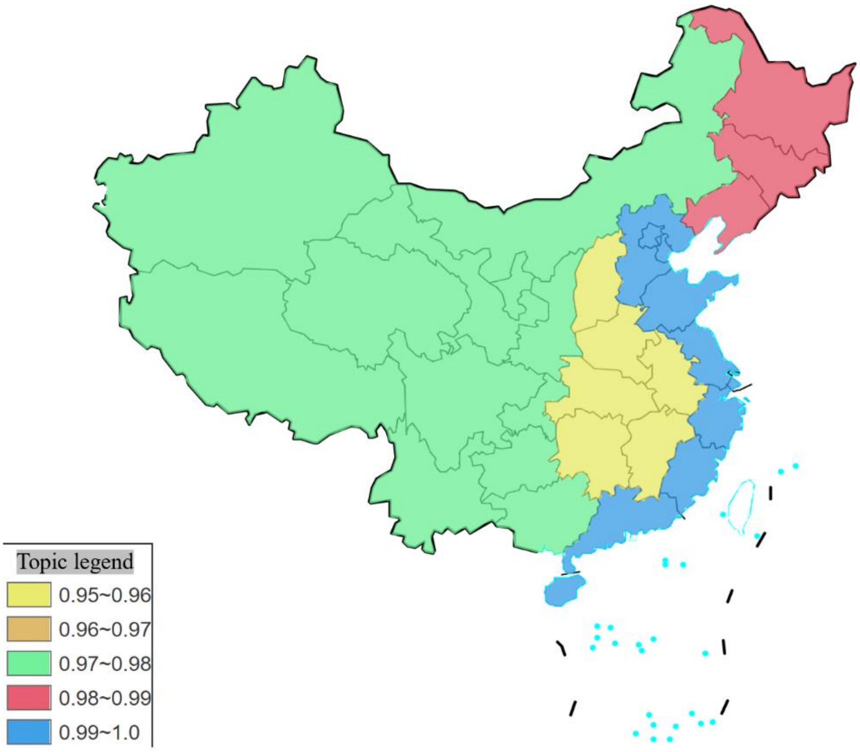

Figure 1. Distribution of technical efficiency by region

Source of the map: http://bzdt.ch.mnr.gov.cn

2)Analyzing the technical efficiency of digital economy-driven green development across provinces and cities, Table 3 presents the technical efficiency scores of China's provinces and cities from 2018 to 2022. To rank the averages, we calculated the arithmetic mean of the technical efficiency for each province and city during the sample period. According to Table 3, it's evident that Beijing, Shanghai, Jiangsu, Fujian, Shandong, Guangdong, Hainan, Henan, Inner Mongolia, Guangxi, Chongqing, Sichuan, Guizhou, Ningxia, Tibet, Xinjiang, and Liaoning are at the forefront, exhibiting optimal performance. This indicates that these provinces and cities have achieved higher efficiency in leveraging the digital economy to drive green development compared to other regions.

Table.3. Technical efficiency of digital economy-enabled green development by province in China, 2018-2022

district	provinces	2018	2019	2020	2021	2022	average value	rankings
eastern part	Beijing	1	1	1	1	1	1	1
	Tianjin	1	1	0.998	0.965	0.937	0.98	7
	Hebei	1	1	1	0.984	1	0.9968	3
	Shanghai	1	1	1	1	1	1	1
	Jiangsu	1	1	1	1	1	1	1
	Zhejiang	0.924	0.962	0.97	0.947	0.94	0.9486	11
	Fujian	1	1	1	1	1	1	1
	Shandong	1	1	1	1	1	1	1
	Guangdong	1	1	1	1	1	1	1
	Hainan Island	1	1	1	1	1	1	1
Central Region	Shanxi	0.916	0.909	0.923	1	1	0.9496	10
	Anhui	0.957	0.943	0.916	0.884	0.893	0.9186	13
	Jiangxi	0.917	0.877	0.86	0.854	0.879	0.8774	14
	Henan	1	1	1	1	1	1	1
	Hubei	1	1	1	1	0.97	0.994	6
	Hunan	1	1	1	0.997	0.974	0.9942	5
Western Region	Inner Mongolia	1	1	1	1	1	1	1
	Guangxi	1	1	1	1	1	1	1
	Chongqing	1	1	1	1	1	1	1
	Sichuan	1	1	1	1	1	1	1
	Guizhou	1	1	1	1	1	1	1
	Yunnan	0.99	1	1	1	1	0.998	2
	Shanxi	0.964	0.923	0.881	0.899	0.929	0.9192	12
	Gansu	0.963	0.978	1	0.954	0.897	0.9584	9
	Qinghai	0.763	0.821	0.87	0.914	0.837	0.841	15
	Ningxia	1	1	1	1	1	1	1
	Xizang	1	1	1	1	1	1	1
	Xinjiang	1	1	1	1	1	1	1
northeastern part of China	Liaoning	1	1	1	1	1	1	1
	Jilin	0.973	1	1	1	1	0.9946	4
	Heilongjiang	0.923	0.981	1	0.998	0.959	0.9722	8

Further, the mean value of the technical efficiency of each province and city in Table 3 during the period of 2018-2022 can be visualised on the distribution graph, as in Figure 2, which clearly shows that the technical efficiency of digital economy-enabled green development in each province and city in China is unevenly distributed, and there will be a situation in which some provinces are very high and some are very low, which suggests that provinces and cities in the process of digital economy development to help greening development This indicates that the provinces and cities have different degrees of assisting greening in the development of the digital economy, especially in Qinghai, which has the lowest technical efficiency among all provinces and cities. Meanwhile, the figure below shows that the efficiency of peripheral regions is generally greater than that of the inner periphery.

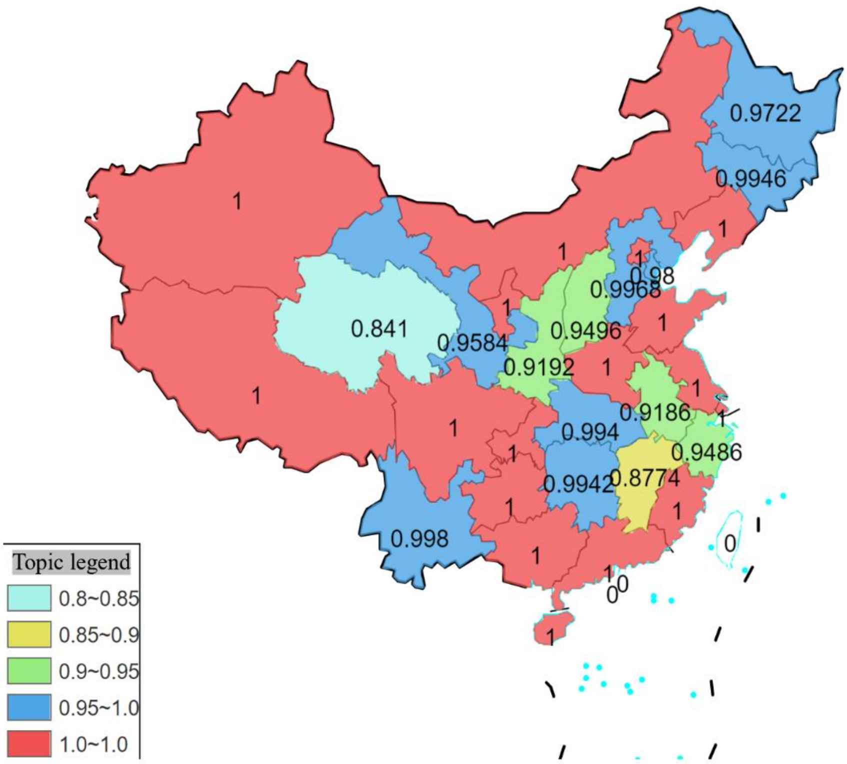

Figure 2. Average technical efficiency of Chinese provinces and cities over the period 2018-2022

Source of the map: http://bzdt.ch.mnr.gov.cn

4.2. Dynamic efficiency analysis

Table .4. Malmquist Index and its Decomposition Indicators by Chinese Provinces and Cities, 2018-2022

year	effch	techch	pech	sech	tfpch
2018-2019	1.0040	1.0135	1.0013	1.0027	1.0174
2019-2020	1.0010	1.0160	0.9988	1.0022	1.0170
2020-2021	0.9996	1.0303	1.0011	0.9985	1.0300
2021-2022	0.9941	1.0399	0.9994	0.9947	1.0335

In Table 4, from the effch of each time period, it can be seen that the period of 2018-2020 is on the rise while the period of 2020-2022 is on the decline, and at the same time, the techch change value of each time period of 2018-2022 can be seen that the production technology has progressed compared with the previous measurement period, and the progress value is increasing, indicating that the production technology is constantly innovating and the digital economy is constantly developing. (value of change) can be seen, the production technology than the previous measurement period has improved, the production frontier can be improved, and the value of progress is increasing, indicating that the production technology is constantly innovating also from the side of the digital economy is constantly being developed. From the above two indicators can be seen, the mathematical economy in the continuous development of the digital economy, but the digital economy empowers the green development efficiency on the whole is decreasing, indicating that the digital economy in the green development of the two paths did not reach a good, coordinated development and complement each other. From the tfpch in each period, it can be seen that the tfpch in all four time periods is greater than 1, and 2020-2021 has increased by 1.2 per cent compared with 2019-2020, which indicates that provinces and cities can make more effective use of the development of the digital economy to obtain relatively more green development results.

Table .5. Calculation of the Malmquist Index for each region by region for the period 2018-2022

eastern part					
	effch	techch	pech	sech	tfpch
2018-2019	1.0054	0.9896	1.0050	1.0004	0.9950
2019-2020	1.0018	1.0280	1.0013	1.0005	1.0299
2020-2021	0.9955	1.0497	0.9956	0.9999	1.0448
2021-2022	0.9943	1.0318	0.9953	0.999	1.0260
Western Region					
	effch	techch	pech	sech	tfpch
2018-2019	1.0074	0.9876	1.0025	1.0048	0.9947
2019-2020	1.0054	1.0084	1.0043	1.0010	1.0139
2020-2021	1.0020	1.0270	1	1.0021	1.0295
2021-2022	0.9869	1.0559	1	0.9869	1.0415
Central Region					
	effch	techch	pech	sech	tfpch
2018-2019	1	1.0236	1	1	1.02367
2019-2020	1	1.0021	1	1	1.00217
2020-2021	1	1.0103	1	1	1.01033
2021-2022	1	1.0188	1	1	1.01883
northeastern part of China					
	effch	techch	pech	sech	tfpch
2018-2019	1	1.1150	1	1	1.1150
2019-2020	1	1.0280	1	1	1.0280
2020-2021	1	1.0036	1	1	1.0036
2021-2022	1	1.0566	1	1	1.0566

Based on the temporal dimension, the Malmquist indices for four regions during 2018-2022 have been individually calculated, as detailed in Table 3. In the eastern region, the change in comprehensive technical efficiency increased from 2018 to 2020, but it relatively decreased from 2020 to 2022. This suggests that despite the favorable development trend of digital economy in the eastern region, it has not been well integrated with green development. In the western region, the change in comprehensive technical efficiency grew in the first three time periods but decreased only in 2021-2022. Meanwhile, the change in comprehensive technical efficiency in the central and northeastern regions remained stable at 1 throughout 2018-2022, indicating that these regions effectively maintained the coordinated development of digital economy and green initiatives. Nationwide, the change in technical efficiency is primarily influenced by the eastern region. In terms of total factor productivity, both the eastern and western regions experienced a decrease from 2018 to 2019 before an increase, suggesting that the output of digital economy enabling green development was relatively low in those years. In contrast, the total factor productivity in the central and northeastern regions continued to increase, indicating that their efforts in leveraging digital economy for green development are becoming increasingly significant. Notably, the change in comprehensive technical efficiency and technological progress in the eastern and western regions exhibit opposing trends, indicating that these regions have not effectively facilitated the coordination between digital economy and green development.

5. Conclusions and recommendations

5.1. Conclusion

1) From a static efficiency perspective, the eastern region exhibits the highest technical efficiency, indicating the most efficient use of digital economy in enabling green development, while the central region demonstrates the lowest technical efficiency. In terms of scale efficiency, none of the four regions have reached optimal production scales, with the central region exhibiting the largest gap from the optimal scale. Specifically, provinces such as Beijing, Shanghai, Jiangsu, Fujian, Shandong, Guangdong, Hainan, Henan, Inner Mongolia, Guangxi, Chongqing, Sichuan, Guizhou, Ningxia, Tibet, Xinjiang, and Liaoning rank at the forefront and are operating at optimal states, indicating a high efficiency of digital economy enabling green development in these provinces. Additionally, the distribution map reveals an uneven distribution of technical efficiency across Chinese provinces and cities in terms of digital economy enabling green development, with peripheral regions generally exhibiting higher efficiency than inner regions.

2) Regarding dynamic efficiency in China, the overall comprehensive technical efficiency experiences an initial rise followed by a decline. During the 2018-2022 timeframe, the techch for each period indicates progress in production technology compared to the preceding measurement period. This progress has led to improvements in the production frontier, with increasing values over time. Notably, the tfpch for all four periods exceeds 1, with a 1.2% improvement from 2020-2021 compared to 2019-2020. This suggests that provinces and cities are making more efficient use of digital economy development, achieving relatively greater green development outcomes.Looking at sub-regions, the change in integrated technical efficiency for both the eastern and western regions follows a pattern of increasing then decreasing from 2018-2022. In contrast, the central and northeastern regions show a more stable trend, with their integrated technical efficiency remaining consistent at 1 during this period. As for total factor productivity, the eastern and western regions experience an initial decrease followed by an increase from 2018-2019, while the central and northeastern regions show a consistent upward trend. Interestingly, the changes in comprehensive technical efficiency and technical progress in the eastern and western regions exhibit opposing patterns.

5.2. Recommendations

As a result of the study, this paper makes the following recommendations:

1) Enhance the overall framework of digital economic advancement and foster a fresh driver for environmentally sustainable growth. Refine the structure of digital economy development, address regional disparities in its advancement, and introduce innovative digital modes of consumption, production, public services, and social governance tailored to local industrial landscapes and developmental necessities. Foster the integration of digital technologies across diverse industries. Identify the unique resources and practical foundations of each region, pinpoint their challenges and strengths in developing the digital economy, and foster deep integration between the digital and real economies. An example would be the establishment of national computational hubs to achieve balanced digital development nationwide.

2) Vigorously promote digital transformation in resource- and industry-driven regions, particularly in the western and northeastern areas were digital infrastructure lags behind. Boosting the construction of new infrastructure, including data centers and the industrial internet, will elevate the region's digitalization level. Foster the emergence of novel digital industries and business models to spawn new economic growth hubs. Enhance the digital proficiency and skills of local talent through education and training, while attracting external digital experts to the region. Optimize resource

allocation, promote energy efficiency and emission reduction, and embark on a path towards sustainable green development.

3) Boosting digital innovation capacity and green low-carbon technological advancements is paramount. Heightening R&D efforts in green and low-carbon technologies is vital in addressing current environmental challenges. Promoting the innovation and application of novel technologies, processes, and materials is essential. Enterprises should be encouraged, through policy incentives and market mechanisms, to adopt green low-carbon technologies, fostering the growth of green industries. Policy support and guidance, along with financial and tax incentives, will be strengthened to foster a conducive environment for digital and green low-carbon technological innovations.

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