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A study of the impact of the digital economy on inclusive green total factor productivity-Mediated by innovative human capital

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Abstract: *Improving inclusive green total factor productivity plays a crucial role in realizing the harmony and unity of economic growth with social equity and environmental protection in a country or region. Using the panel data of 30 provinces in China from 2011 to 2020, and the impact of the digital economy on the inclusive green total factor productivity (IGTFP)and its decomposition term is examined theoretically and empirically, and the mediating role played by innovative human capital is examined. The study finds that: the development of digital economy can significantly promote the growth of IGTFP and mainly promote inclusive green technological progress, and the conclusions still hold after a series of robustness tests; the analysis of heterogeneity finds that the development of digital economy plays a more obvious role in improving the growth of IGTFP in the central and western regions; the results of the analysis of the mechanism show that the digital economy indirectly improves regional IGTFP through the accumulation of innovative human capital. In this regard, we should accelerate the construction of a perfect digital infrastructure, focus on the cultivation of innovative human capital, and formulate precise institutional policies.*

Keywords: *digital economy, innovative human capital, inclusive green total factor productivity, mediating effect*

1. Introduction

China's economy has realized a leaping development and is gradually moving towards the stage of high-quality development, but China is still facing such problems as unbalanced and inadequate development, uneven urban-rural development, inequitable income distribution, and ecological and environmental protection. How to effectively alleviate the environmental problems caused by rapid economic growth, whether to narrow the urban-rural income gap while promoting economic growth so as to realize social equity have become important issues that need to be resolved in China. Inclusive Green Total Factor Productivity (IGTFP) includes the triple attributes of environment, equity and efficiency, and improves the distribution structure, social inclusiveness and ecological environment quality while realizing sustained economic growth in the new era, so as to promote the coordinated development of China's economy, society and environment in a comprehensive manner. At present, China has entered a development stage with digital economy as the core driving force. However, the digital economy will also bring some environmental problems, because the digital economy relies on a large number of electronic equipment and products, which will generate a certain amount of pollution emissionsin the process of using these equipment and products. The digital economy will also create a digital divide between regions, which is due to the existence of different digitally-adapted groups with very different levels of digital skills. This makes them very different in terms of sharing the dividends of the digital economy. The digital economy is not only changing the structure and development mode of traditional industries, but also reshaping the face and function of human capital. The digital economy is triggering the demand for innovation of economic agents, and the demand for innovative talents has increased dramatically in various regions. Although the scale of China's human capital is large, there is still a lack of innovative talents.

2. Literature Review

Research on the development of the digital economy on inclusive green growth remains divided. A portion of scholars agree that the development of the digital economy has a positive impact on the

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growth of IGTFP and can promote the sustainable development of the country. Liu et al.[1] (2022) use machine learning algorithms to find that digitalization represented by digital technologies such as the Internet of Things is a core driver of inclusive green development in cities. Zhu et al.[2] (2023) explored that digital economic policies can enhance inclusive green growth, reflecting the important role of balancing ecological environment, social equity and economic efficiency. Li et al.[3] (2023) empirically examined that the construction of digital infrastructure can promote inclusive green growth in local areas. Economic agglomeration plays a mediating role in it, and as the degree of economic agglomeration grows,it is shows a U-shaped characteristic of inhibiting and then promoting. However, some scholars[4] believe that rapid development of the digital economy will lead to the "digital divide", "technological unemployment" and "platform monopoly" and other problems, which will exacerbate the risk of social income imbalance.

In summary, domestic and foreign scholars have made certain achievements in the research on the relationship between digital economic development and IGTFP, but there are still differences, that is, there is no unified view on whether digital economic development inhibits or promotes inclusive green growth. Based on this, we explore the effect of the digital economy on the IGTFP and its decomposition term, and explore the role of innovative human capital. The main contributions of this paper are as follows: first, the inclusive technical progress index and the inclusive technical efficiency index in IGTFP are decomposed for research, and the impact of digital economy on their decomposition terms are explored separately, so that the conclusions are more rich and specific. The second is to incorporate "digital economy development - innovative human capital - IGTFP" into a unified research framework, introduce innovative human capital as a mediating variable, and explore its transmission role in the digital economy's impact on IGTFP. This study aims to fill the gaps in the existing literature and provide guidance to policymakers, so as to help enterprises and society better adapt to realize the goal of sustainable development.

3. Theoretical Analysis

In this paper, inclusive green total factor productivity (IGTFP) is decomposed into inclusive green technological progress (IGTC) and inclusive green technological efficiency (IGEC), and the decomposition indicators of IGTFP focus more on the environmental friendliness and social fairness of the production activities while measuring the efficiency of the production[5] .

3.1 Effects of the digital economy on inclusive green total factor productivity

IGTC represents advanced production technology to promote the overall production frontier to move outward to rise, by measuring the changes in the optimal output of the decision-making unit, and then determine whether the regional technological level is upgraded. The digital economy is presenting an economic development model with data as the core elemental input and innovation as an important means of development, which, while promoting rapid growth in economic efficiency and socially inclusive development, is able to reduce pollution and energy consumption and promote IGTFP growth[6] . The digital economy, which is centered on the upgrading of digital transformation of industries, and the development of digital industrialization, has increased employment opportunities by improving the efficiency of communication, breaking through the limitations of space and time, and narrowing the income gap between urban[7] and rural areas[8] to promote inclusive green technological progress. Specifically, the digital economy breaks the spatial boundaries of distance, which not only reduces the obstacles to communication but also creates more jobs and more employment opportunities for members of the society, and provides realistic possibilities and brand new opportunities for the people to choose the appropriate employment methods, thus expanding the employment opportunities of all kinds of people and expanding the employment opportunities of all kinds of people. It also provides real possibilities and new opportunities for people to choose suitable employment methods, thus expanding income channels and wealth creation space for workers of all classes, optimizing the pattern of social income distribution, and narrowing the income gap between urban and rural areas[9]. The level of technological innovation in the region as a whole will be raised, effectively deepening the division of labor in production, and thus promoting inclusive green technological progress.

Inclusive technological efficiency is manifested in such areas as diffusion and extension under existing technological conditions and increased productivity through improved management processes and working methods. Specifically, with digitalization oriented to connect reality with the virtual space of the network, workers can obtain information through the internet. Not only can reduce labor job

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search costs, but also effectively avoid the asymmetry of information brought about by the non-equalization of opportunities. The labor force can easily and quickly obtain labor supply and demand information at a lower cost, accelerate the flow to non-agricultural industries, and enhance the labor force employment rate, thus optimizing the urban and rural labor force allocation, which increaset on the efficiency of inclusive green technology. The digital economy has the characteristics of nearly zero marginal cost and obvious network effect, which strengthen its technological impact on traditional industries, mainly manifested in the impact on the production and operation mode of traditional industries, and the traditional economy will be crowded out . Thus the digital economy gains a greater market advantage , eventually acquires a monopoly position, and uses its market dominance or monopoly position to the detriment of consumer and social welfare, to the detriment of the efficiency of IGEC[10] .

Hypotheses H1: The digital economy contributes to IGTFP growth and mainly promotes inclusive green technological progress.

3.2 Mechanisms of the digital economy's impact on inclusive green total factor productivity

The digital economy facilitates the accumulation of innovative human capital. The digital economy emphasizes to improve efficiency. This makes information sharing, transactions and communication faster and more convenient. A large number of industries have been deeply integrated with artificial intelligence technology, and more and more enterprises and organizations have begun to realize digital transformation, promoting digital technology to reshape traditional industries in an all-around, multi-angle, and all-chain manner, and putting forward higher requirements for workers' skill levels, innovative thinking, and creativity, which has led to in the level of workers' knowledge and their ability to learn. The knowledge level and learning ability of laborers have been improved, and their cognitive and creative abilities have been strengthened. The digital economy will lead to in the government's investment in education, which will make it easier for people to acquire and update knowledge and improve their skills, thus generating the effect of innovative human capital accumulation[11].

Creative human capital is conducive to increasing IGTFP. Creative human capital is a higher level of human capital, which not only has the general attributes of human capital, but also possesses scarce production allocation and technology absorption, innovative thinking ability[12] that has the qualities of increasing long-term marginal returns and output multiplier effects[13]. Innovative human capital is an important carrier of knowledge creation and technological progress.Innovative human capital leads to a decrease in labor costs, providing more innovative talents who can propose new and more inclusive management methods and green production technologies. A shift in the direction of technological progress driven by technological innovation and a rapid increase in the skill premium can realize an efficient combination of factors of production, which in turn improves the productivity of their human capital, drives technological progress and increases IGTFP.

Hypotheses H2. H2: The digital economy enhances IGTFP growth through the accumulation of innovative human capital.

4. Research Design

4.1 Modeling

To further verify the impact of the digital economy on IGTFP and its decomposition terms , IGTFP is divided into inclusive green technological progress (IGTC) and inclusive green technological efficiency (IGEC).The model is as follows:

$$\mathrm{IGTFP}_{it} = \beta_0+\beta_1 DEG_{\mathrm{it}}+\beta_2 X_{\mathrm{it}} + \mu_i+v_t+\varepsilon_{\mathrm{it}} \tag{1}$$

$$\mathrm{IGTC}_{it} = \beta_3+\beta_4 DEG_{\mathrm{it}}+\beta_5 X_{\mathrm{it}} + \mu_i+v_t+\varepsilon_{\mathrm{it}} \tag{2}$$

$$\mathrm{IGEC}_{\mathrm{it}} = \beta_6+\beta_7 DEG_{\mathrm{it}}+\beta_8 X_{\mathrm{it}} + \mu_i+v_t+\varepsilon_{\mathrm{it}} \tag{3}$$

IGTFP_{it} is the inclusive green total factor productivity of province i at time t, reflecting the three attributes of efficiency, equity and greenness. IGTC_{it} is the inclusive green technological progress in province t. IGEC_{it} is the inclusive green technical efficiency in province t. DEG_{it} is the digital economy development in province i at time t. X_{it} is a series of control variables including urbanization rate, government intervention, foreign direct investment, environmental regulation and industrial structure. β_0 is the constant term, μ_i is the individual effect of province, ν_t is the time effect, ε_{it} is the random disturbance term of the regression equation.

In order to further identify whether the digital economy can achieve IGTFP growth through the accumulation of innovative human capital, hypothesis H2 is tested. We refer to Wen et al.[14] (2004) for the mediation effect test, and constructs the following two models based on Eq. (1):

$$M_{it} = \alpha_0+\alpha_1 DEG_{it}+\alpha_2 X_{it} + \mu_i+v_t+\varepsilon_{it} \tag{4}$$

$$\mathrm{IGTFP}_{it} = \gamma_0+\gamma_1 DEG_{it}+\gamma_3 M_{it} + \gamma_4 X_{it} + \mu_i+v_t+\varepsilon_{it} \tag{5}$$

where M_{it} serves as the mediator variable for innovative human capital (IHC for short).

4.2 Description of variables and data sources

1) Explained variable: inclusive green total factor productivity (IGTFP), this paper mainly draws on Li et al.[5] (2021) and Chen et al.[15] (2014) research. It is more in line with the themes of "greenness" and "fairness" emphasized. A GML productivity index based on the directional distance function of the super-efficient SBM with undesired outputs is used to measure the IGTFP. Drawing on the study of Oh et al.[16] (2010), the IGTFP index is further divided into inclusive green technical progress (IGTC) and inclusive green technical efficiency (IGEC). Drawing on the study of Qiu [17] (2008), the IGTFP is converted into the final adjusted IGTFP using the cumulative multiplication method with 2011 as the base period for measurement. Specific indicators are shown in Table 1.

Table 1 Selection of IGTFP indicators

Name	Primary indicators	Secondary indicators	Meaning of the indicator
IGTFP	Input indicators	labor input	Year-end employment by province
		capital investment	Capital stock
		Energy inputs	Total energy consumption
	Output indicators	Expected outputs	Real GDP
		Non-expected outputs	Chemical oxygen demand
			Industrial sulphur dioxide emissions
			Urban unemployment rate
			Disposable income ratio of urban and rural residents

2) Core explanatory variables. Drawing on Zhao et al.[18] (2020) and Liu et al.[19] (2021), the digital economy level indicators are divided into three aspects(see Table 2). At present, the subjective and objective assignment methods are mainly used to measure . This article uses the entropy weight method to measure the Digital Economy Index (DEG).

Table 2 Selection of digital economy indicators

name	norm	Meaning of the indicator
DEG	digital infrastructure	Number of domain names
		Number of Internet broadband access subscribers
		Cell phone subscribers per 100 population
	digital industrialization	Software and information services revenue
		Percentage of employees in computer services and software
		Total telecommunication services
	Industrial Digitization	Digital Inclusive Finance Index
		Percentage of websites owned by enterprises
		express mail
		E-commerce sales

3) Mediating variables. Drawing on the research of Wang et al.[20] (2020), innovative human capital is measured by the number of R&D personnel per 100 employed people in each region.

4) Control variables. Urbanization level (UBR): measured by the share of urban population in the year-end resident population in each region. Government intervention (GOV): measured by the ratio of government fiscal expenditure to GDP in each region. Foreign Direct Investment (FDI): measured by the ratio of FDI to GDP in each region. Industrial Structure (STRUG): measured by the value added of the tertiary sector as a percentage of GDP in each region. Environmental regulation (ER): measured by the proportion of completed investment in industrial pollution control to the value added of secondary industry.

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4.3 Data sources and descriptive statistical analysis

30 provinces are selected as the research objects in this paper from 2011 to 2020, and a total of 300 panel data sets are selected. The data are taken from China Statistical Yearbook, China Energy Statistical Yearbook, China Environmental Statistical Yearbook, and provincial statistical yearbooks. The indicators of digital inclusive finance development are from the Digital Finance Research Center of Peking University. Missing values are filled in by interpolation. The descriptive statistics of relevant variables are shown in Table 3.

Table 3 Results of descriptive statistics

variable name	notation	N	average value	standard deviation	minimum values	maximum values
Inclusive green total factor productivity	IGTFP	300	1.337	0.423	0.531	3.989
Inclusive green technological advances	IGTC	300	1.201	0.309	0.288	2.57
Inclusive green technology efficiency	IGEC	300	1.125	0.362	0.494	5.281
Level of the digital economy	DEG	300	0.1323	0.1252	0.0079	0.7923
Innovative human capital	IHC	300	0.7508	0.6819	0.1388	3.759
urbanization level	UBR	300	0.583	0.125	0.3503	0.896
government intervention	GOV	300	0.242	0.077	0.106	0.451
overseas foreign direct investment	FDI	300	0.021	0.019	0.001	0.121
industrial structure	STRUG	300	0.481	0.105	0.175	0.829
environmental regulation	ER	300	0.290	0.283	0.00451	2.451

5. Analysis of empirical results

5.1 Analysis of baseline regression results

First, this paper chooses a two-way fixed effects model to estimate the impact of digital economy development on IGTFP. The empirical results are shown in Table 4. First of all, the regression coefficient of digital economy on IGTFP is 1.422 and significantly positive at the 1% level, which indicates that the digital economy has a significant positive impact on IGTFP, and for every unit of growth in the digital economy, IGTFP will increase by 1.422 units. Further exploring the impact of the digital economy on the decomposition term of IGTFP, the digital economy affecting green technological progress is 1.389 and significant at the 1% level. The regression coefficient of digital economy affecting inclusive green technical efficiency is 0.753 and the regression result is not significant. It shows that the digital economy promotes IGTFP growth mainly by promoting IGTC progress. The digital economy can achieve the harmonious development of economy and ecology, also maximize its externalities, promote social equity, and promote the growth of regional IGTFP. Overall, the empirical analysis results in Table 4 confirm the research hypothesis H1 proposed in the theoretical analysis of this paper.

Table 4 Benchmark regression results

variant	(1)	(2)	(3)
	IGTFP	IGTC	IGEC
DEG	1.422***	1.389***	0.753
	(0.395)	(0.299)	(0.498)
control variables	control	control	control
Constant	-1.182	-0.675	2.029**
	(0.727)	(0.550)	(0.917)
Time/area	control	control	control
R-squared	0.592	0.472	0.153
Number of id	30	30	30

Note: Standard errors in parentheses, *, ** and *** indicate significance at the 10%, 5% and 1% levels, respectively. Same as below.

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5.2 Robustness Tests

The robustness of the baseline regression results was tested by replacing explanatory variables and shortening sample time. The results are shown in Table 5, and the specific steps are as follows:

(1) Replacement of explanatory variables. The digital inclusion index is estimated by replacing the level of digital economy development. The regression results of the digital economy on IGTFP and its decomposition term are still same with the benchmark regression, suggesting that the conclusion that the digital economy can enhance the growth of IGTFP and mainly promote inclusive green technological progress is robust. (2) Reducing sample time. The data of 2011 and 2012 are all excluded, and the sample data of 2013-2020 are used for estimation. The regression results of the digital economy on IGTFP and its decomposition terms remain consistent with the previous section.

Table 5 Robustness test results

variant	(1)	(2)	(3)	(4)	(5)	(6)
	ITFP	IGTC	IGEC	ITFP	IGTC	IGEC
DEG	0.00457*	0.00695***	0.00112	1.052**	1.262***	0.758
	(0.00236)	(0.00177)	(0.00294)	(0.507)	(0.364)	(0.680)
control variables	control	control	control	control	control	control
Constant	-1.182	-0.675	2.029**	-1.333	-0.910	2.755**
	(0.727)	(0.550)	(0.917)	(1.017)	(0.730)	(1.364)
Time/area	control	control	control	control	control	control
R2	0.592	0.472	0.153	0.537	0.445	0.124
id	30	30	30	30	30	30

5.3 Endogeneity analysis

Considering that there may be endogeneity problems such as omitted variables and reverse causality between the digital economy and IGTFP, this paper further employs instrumental variable estimation to mitigate the endogeneity problem. Therefore, drawing on the research of Kong et al. [21] (2023),using the lag period of DEG as an instrumental variable for regression, Table 6 shows that the impact of the digital economy on IGTFP and inclusive green technology progress is significantly positive at the 1% level, respectively. This indicates that, after considering endogeneity issues, the digital economy still significantly improves the growth of IGTFP.

Table 6 Results of endogenous analysis

variant	(1)	(2)	(3)
	IGTFP	IGTC	IGEC
DEG	1.557***	1.514***	0.616
	(0.389)	(0.353)	(0.611)
control variables	control	control	control
Constant	-8.167***	-6.984***	4.425
	(1.781)	(2.151)	(3.205)
Time/area	control	control	control
R-squared	0.605	0.541	0.377
id	30	30	30

5.4 Analysis of regional heterogeneity

Different levels of digital economic development in different regions may also have different impacts on the results. The test results for the eastern region are shown in columns (1)-(3) of Table 7. The test results for the central and western regions are shown in columns (4)-(6) of Table 7. The results show that the development of digital economy in the eastern region has a positive but not significant impact on IGTFP, and in the central and western regions has a significant positive impact on IGTFP. The reason for the difference between the eastern and central and western regions may be that compared with the eastern region, the central and western regions started the development of low-carbon economy later, the problem of urban-rural development imbalance is more prominent, and the level of development of the digital economy has a higher room for improvement of IGTFP[22]. The eastern region's low-carbon economy is relatively developed, with a high employment rate, high social inclusiveness, and relatively sufficient digital resources, whose marginal benefits for economic development may be lower.

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Table 7 Results of heterogeneity analysis

variant	(1)	(2)	(3)	(4)	(5)	(6)
	IGTFP	IGTC	IGEC	IGTFP	IGTC	IGEC
DEG	0.679	0.804*	0.654	6.367***	3.273***	0.644
	(0.535)	(0.443)	(0.771)	(1.503)	(0.844)	(1.615)
control variables	control	control	control	control	control	control
Constant	-2.629**	-3.177***	4.049**	1.184	1.672**	0.183
	(1.514)	(1.492)	(2.514)	(1.253)	(0.704)	(1.347)
Time/area	control	control	control	control	control	control
R-squared	0.656	0.563	0.174	0.619	0.558	0.256
id	13	13	13	17	17	17

5.5 Analysis of impact mechanisms

In order to explore the question of how the digital economy affects IGTFP, attempts to empirically test the transmission mechanism proposed by H 2 using a mediated effects model. According to column (3) of Table (8), it shows that the digital economy and innovative human capital have a positive effect on IGTFP and are significant at the 10% level. The inclusion of both digital economy and innovative human capital variables in the model has made significant contributions to the growth of IGTFP. This suggests that the digital economy can simultaneously contribute to IGTFP growth by promoting the accumulation of innovative human capital.

Table 8 Estimation results of the mediated effects model

variant	(1)	(2)	(3)
	IGTFP	IHC	IGTFP
DEG	1.422***	1.708***	0.919*
	(0.395)	(0.141)	(0.494)
IHC			0.295*
			(0.174)
control variables	control	control	control
Constant	-1.182	0.266	-1.261*
	(0.727)	(0.260)	(0.726)
Time/area	control	control	control
R-squared	0.592	0.720	0.596
id	30	30	30

6. Conclusions and Implications of the Study

Improving IGTFP is the main direction for China to continuously form new quality productivity in the future. Based on the theoretical analysis, this paper evaluates the causal effects of the digital economy on IGTFP and its decomposition term, as well as the role mechanism of innovative human capital in it, using the panel data of 30 provinces in China from 2011 to 2020, and the main conclusions are as follows. The main conclusions are as follows: (1) The digital economy can significantly enhance IGTFP. Further analyzing the IGTFP decomposition terms, it is found that the digital economy mainly positively promotes inclusive green technological progress. (2) The impact of the digital economy on improving IGTFP is regionally heterogeneous, with a greater impact on the central and western regions than on the eastern region. (3) The mediating effect of innovative human capital indicates that there is a transmission mechanism of "digital economy development - innovative human capital - IGTFP". The digital economy enhances the growth of IGTFP through the accumulation of regional innovative human capital. Therefore, this paper proposes the following policy implications:

Firstly, in the context of the economic downturn, governments can formulate policies to support digital technological innovation, such as providing incentives such as research and development funding, tax reductions or preferential policies, in order to encourage enterprises and institutions to carry out digital technological innovation, which will increase productivity levels, enhance the efficacy of local social safeguard governance and increase employment opportunities, thereby enhancing IGTFP. The government can promote the establishment of an open and interconnected digital service platform to facilitate the seamless connection of all links in the industrial chain, and improve overall efficiency by sharing resources and optimizing production processes. The government needs to strengthen the regulation of the digital economy to prevent various types of risks and standardize the operation of the digital economy. In addition, the government can organize digital transformation, including digital production processes, digital supply chain management, and digital marketing. Through digital transformation, enterprises and organizations can help improve digital skills, increase productivity, reduce resource waste and achieve greener, more inclusive and sustainable production methods, thus enhancing IGTFP.

Secondly, local governments should formulate differentiated strategies based on their own development needs and actual conditions, promoting economic growth, focusing on equity and green efficiency to advance China's development. For the central and western regions of China, the governments of these regions should formulate relevant policies and investment support to drive the digitization of society development. For China's eastern region, it is necessary to strengthen the problem orientation, formulate precise institutional policies for specific situations, further highlight the characteristics of all-round, broad field and multi-level openness, and realize a higher level of openness, which will in turn expand the scope of its application. The government can strengthen cooperation between the eastern region and other regions to foster synergistic regional development. This includes strengthening industrial cooperation, technological exchanges and the flow of talents , so as to achieve the optimal allocation of resources and mutual benefits.

Thirdly, to give full play to the leading and supporting role of innovative human capital, innovative talents should be cultivated in a targeted and forward-looking manner. To stimulate the technological innovation effect of innovative human capital, the government should also increase investment in independent innovation, allowing innovative talents to make breakthroughs in pollution control and new energy technologies, thereby promoting the improvement of energy efficiency.To create an ecological environment for high-level innovative talents, the government can promote cooperation among enterprises, universities and research institutions to establish an industry-university-research alliance or innovation ecosystem. On the other hand, to create a high-level innovative talent ecosystem, the government can promote cooperation among enterprises, universities and research institutions, and establish an industry-university-research alliance or innovation ecosystem. Such cooperation can promote knowledge flow, technology transfer and talent cultivation, and emphasize the cultivation of green concepts and low-carbon awareness of innovative talents, guiding them to energy conservation, and promoting the enhancement of IGTFP.

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