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The Impact of AI Technology Innovation on Manufacturing Energy Intensity

Ye Tong
School of Finance and Economics, Jiangsu University, Jiangsu, China
Email address: 2789644971@qq.com

Abstract— *With the continuous integration of digital technology into people's lives, facing the increasingly prominent energy constraints in economic and social development, this project studies its impact on energy intensity of the manufacturing industry based on the current situation of AI technology innovation in 34 countries, and analyzes the specific path of the impact of AI technology innovation on energy intensity of the manufacturing industry from the perspective of industrial structure and total factor productivity, give full play to the advantages of AI technology innovation in the manufacturing industry, promote the deep integration of AI technology and manufacturing industry, and play an important role in economic and social development as well as the reduction of energy intensity*.

Keywords— *Artificial Intelligence, Digital Technology, Technological Innovation, Manufacturing Eenergy Intensity, Fixed Effect Model*.

I. INTRODUCTION

In the digital age, digital technology is closely related to people's lives. Digital technology can build a more direct and efficient network, improving economic efficiency. The digital transformation of the manufacturing industry under the drive of Industry 4.0 is an inevitable trend. China attaches great importance to the development of digital technology and manufacturing industry. The Fifth Plenary Session of the 19th Central Committee of the Communist Party of China proposed to "accelerate digital development". The "14th Five-Year Plan for the Development of the Digital Economy" also emphasizes the "promotion of industrial digital transformation". Artificial intelligence, as an important role in digital technology, was highlighted in China's 2017 "New Generation Artificial Intelligence Development Plan". The 19th National Congress of the Communist Party of China clearly stated that artificial intelligence should be relied upon to lead the transformation of the manufacturing industry and promote high-quality economic development. Various regions in China have also put forward development plans for artificial intelligence and related policies for high-quality development. The Vice Minister of the Ministry of Industry and Information Technology stated that the focus should be on intelligent manufacturing to promote the deep integration of the new generation of information technology such as artificial intelligence with the manufacturing industry. Energy intensity is one of the most commonly used indicators to compare the comprehensive energy utilization efficiency of different countries and regions, reflecting the economic benefits of energy utilization. In China's 11th Five-Year Plan, the "energy intensity" goal was clearly defined, requiring a 20% reduction in energy consumption per unit of GDP compared to 2005 to address the increasingly prominent energy constraints and environmental issues in economic and social development. Through innovation in artificial intelligence technology, manufacturing industry energy intensity can be adjusted to ensure simultaneous development and environmental protection. Does innovation in artificial intelligence technology have an impact on the energy intensity of the manufacturing industry, and what is the mechanism of this impact? How can the development of artificial intelligence technology in the manufacturing industry ensure that China's energy intensity in manufacturing has an advantage over the comprehensive energy utilization efficiency of different countries and regions? This project aims to conduct research to solve these two scientific questions.

II. LITERATURE REVIEW

A. Impact of AI on the Manufacturing Industry

Some scholars believe that artificial intelligence promotes the rationalization and advancement of the manufacturing industry, leading to high-quality development[1][2]. Artificial intelligence, as a systematic methodology and discipline, focuses on developing, validating, and deploying various machine learning algorithms with sustainable performance for industrial applications, providing solutions for industrial applications[3]. In the furniture manufacturing sector, artificial intelligence provides technical solutions for AI applications. When furniture manufacturing faces issues such as low production efficiency and lack of product innovation, the development of artificial intelligence management systems helps with information transfer and control, improving the quality and production efficiency of furniture products[4]. The emergence and rapid development of artificial intelligence technology have provided a foundation for highly automated production in the plywood manufacturing industry, replacing outdated production modes and automatically repairing defects on plywood[5].

B. Factors Influencing Manufacturing Industry Energy Intensity

The factors influencing energy intensity in the manufacturing industry have been a hot topic of research for both domestic and foreign scholars. Existing studies explore the impact on energy intensity through aspects such as green development and technological progress. Hou Jian et al. conducted a systematic analysis of the heterogeneity structure of China's manufacturing industry's green transformation based on the Super-SBM and dynamic panel threshold models, and explored the impact of green transformation on energy

intensity from an environmental regulation perspective[6]. Zhang Rui et al. established a panel data model to empirically analyze the influences of environmental regulations and economic diversity on energy intensity [7]. Li Tailong et al. constructed a transcendent logarithmic cost function model and used the seemingly unrelated regression method to study the biased factors of different sources of technological progress in China and their effects on energy intensity[8]. Liu Huihui and Xu Chao studied the reasons for the changes in China's energy intensity from the perspective of biased technological progress using the LMDI index decomposition method and regression analysis, providing an explanation for the continuous decline in China's energy intensity[9]. Some commonly mentioned factors influencing energy intensity in existing literature include industrial structure, technological innovation, economic development level, trade openness, urbanization, foreign direct investment, and energy consumption structure.

C. *Relationship between Technological Innovation and Manufacturing Industry Energy Intensity*

Innovation is the soul of a nation's progress and the inexhaustible driving force behind a country's prosperity. Economic growth and social progress cannot be achieved without innovation, and technological innovation plays a particularly important role. At the same time, technological innovation needs to be constrained in terms of energy utilization. Zhuang Zhiqiao used the spatial Durbin model with dual fixed effects to test that regions with higher innovation capabilities tend to have lower energy utilization intensity, while regions with lower technological innovation capabilities tend to have higher energy utilization intensity[10]. This indicates the impact of technological innovation on enterprise energy intensity. Many scholars have studied the impact of technological innovation on energy intensity, including research on green technological innovation and energy intensity. Gu Huidong et al. studied the impact of green technology on carbon emissions[11], while Xu Jianzhong et al. examined the influence of green technology innovation on energy intensity under different environmental regulations[12]. Energy technology innovation, technological innovation models, the mechanism and effects of technological innovation on enterprise energy consumption have all received attention, indicating that technological innovation is an important means to reduce enterprise energy intensity.

III. RESEARCH DESIGN

A. *Theoretical Analysis and Research Hypotheses*

1) *The Direct Impact of AI on the Energy Intensity of the Manufacturing Industry*

Artificial intelligence provides automated and intelligent production and management models for the manufacturing industry, thereby improving product production efficiency and resource allocation efficiency, reducing costs, and reducing unnecessary resource waste. Technological innovation is an important means to reduce the energy intensity of enterprises. Artificial intelligence can aggregate and process a large amount of data, build efficient network systems, help the green transformation of manufacturing industry, and reduce energy consumption. In this regard, this article proposes:

H1: Innovation in artificial intelligence technology can significantly affect the energy intensity of the manufacturing industry.

2) *The Indirect Impact of AI on Energy Intensity in the Manufacturing Industry*

a) The Mesomeric Effect of Industrial Structure

Against the backdrop of rapid integration of artificial intelligence and industry, scholars have begun to pay attention to the impact of artificial intelligence on industrial structure. Artificial intelligence technology innovation provides technical support for the manufacturing industry, improves industrial production efficiency and resource allocation efficiency. The integration of artificial intelligence and traditional industries has given rise to a series of emerging industries, promoting the advancement and rationalization of industrial structure. There is a clear correlation between changes in industrial structure and energy intensity in the manufacturing industry. Although scholars do not have a unified analysis of the results, reasonable industrial structure adjustments can reduce energy intensity. Regarding this, this article assumes that:

H2: Innovation in artificial intelligence technology significantly affects the energy intensity of the manufacturing industry through industrial structure.

b) Mesomeric Effect of Total Factor Productivity

Technological progress and manufacturing upgrading are the main channels to play the role of "inhibition" of the digital economy. Artificial intelligence technology innovation can improve the production efficiency of products. Total factor productivity is an indicator to measure the efficiency of economic growth. The level of economic development has a significant impact on the energy intensity of manufacturing. In response, this article proposes:

H3: AI significantly affects the energy intensity of manufacturing industry through Total factor productivity.

B. *Model Design*

1) *Benchmark Model*

To investigate the direct impact of artificial intelligence technology innovation on energy intensity in the manufacturing industry, the following model is constructed:

$$EI = \alpha_0 + \alpha_1 AI + \alpha_2 Ctrl + \mu + \varepsilon$$

Among them, EI represents the energy intensity of the manufacturing industry, AI represents artificial intelligence technology innovation, and Ctrl represents the control variable, μ、ε represents fixed effects and random error terms.

2) *Mesomeric Effect Model*

In order to explore the impact of Mesomeric effect on this model, the following model is constructed:

$$EI = \lambda_0 + \lambda_1 AI + \lambda_2 Ctrl + \mu + \varepsilon$$
$$M = \kappa_0 + \kappa_1 AI + \kappa_2 Ctrl + \varphi + \gamma$$
$$EI = \beta_0 + \beta_1 AI + \beta_2 M + \beta_3 Ctrl + \omega + \nu$$

M is the intermediary variable, representing industrial structure and Total factor productivity.

C. *Variable and Data Description*

1) The Dependent Variable - Manufacturing Energy Intensity EI

Based on the definition of energy intensity in a large number of literature, this article ultimately decides to represent the energy intensity of the manufacturing industry with the proportion of total energy consumption to total output. WIOD, as a world input-output database, is representative in terms of manufacturing data related to energy consumption. Therefore, this article selects data from WIOD to determine the energy intensity of various manufacturing industries.

2) Core Explanatory Variable - AI

Most existing research uses patents to represent technological innovation. The OECD, in collaboration with over 100 countries, is a global policy forum. This article exports technology patents related to artificial intelligence from its database as indicators of AI technological innovation.

3) Control variables

The control variables selected in this article include economic development level (GDP, defined as per capita real GDP), energy consumption structure (ECO, defined as the proportion of individual energy consumption to total energy consumption), foreign direct investment (FDI, defined as the ratio of foreign direct investment to GDP), degree of trade openness (TO, defined as the ratio of total import and export to GDP), urbanization (Urban, defined as the proportion of urban population to total population). The energy consumption structure data is taken from the IEA, while the rest are taken from the WDI.

4) Mediating Variables

Industrial structure IS is defined as the proportion of manufacturing added value in GDP, which is taken from the WDI, and Total factor productivity is taken from the Penn table. It is divided into Total factor productivity level TFP1 under the current PPP and welfare related Total factor productivity level TFP2 under the current PPP.

IV. Empirical Analysis

A. Descriptive Statistics

In order to prevent the impact of Outlier on the research results, this paper first shrinks the tail of the data, conducts extreme value processing at 1% and 99% quantiles, and then conducts descriptive statistics on the data. The results are shown in Table 1.

Table 1

Variable	Obs	Mean	Std.dev.	Min	Max
lnEI	7,332	-17.21045	2.265156	-22.77899	-11.83437
AI	7,344	71.51324	192.3877	0	974.6
GDP	7,344	29794.37	20134.88	1162.499	82997.69
FDI	7,344	4.146484	6.577937	-5.061605	37.60373
TO	7,344	27220.86	20892.06	4.181204	82796.58
Urb	7,344	71.89956	13.72037	30.587	97.744
ECO	7,344	.8432497	.1134159	.5999651	1
IS	7,344	15.86489	5.525764	6.608333	32.11941
TFP1	7,344	.7709297	.2001477	.3913531	1.372791
TFP2	7,344	.7332097	.1589023	.3688707	1

B. Correlation Analysis and Multicollinearity Test

This paper has also conducted correlation analysis and tested Multicollinearity of the data. It can be seen from Table 2 that the correlation between the variables is significant, so we need to control these variables. Among them, the level of economic development and foreign trade are highly correlated. We will further conduct Multicollinearity test. It can be seen from Table 3 that the VIF is less than 5. According to the judgment criteria of Multicollinearity, The variable indicators selected in this paper do not have Multicollinearity.

Table 2

	lnEI	AI	GDP	FDI	TO	Urb	ECO
lnEI	1.0000						
AI	0.1146***	1.0000					
GDP	-0.1343***	0.1355***	1.0000				
FDI	-0.0258**	-0.1480***	0.0995***	1.0000			
TO	-0.1264***	0.1264***	0.8801***	0.0644***	1.0000		
Urb	-0.1067***	0.2457***	0.5086***	-0.0239**	0.4555***	1.0000	
ECO	-0.0200*	0.3411***	0.4092***	0.1154***	0.3470***	0.3229***	1.0000
****** p<0.01, ** p<0.05, * p<0.1***							

Table 3

Variable	VIF	1/VIF
GDP	4.97	0.201197
TO	4.45	0.224925
Urb	1.43	0.700120
ECO	1.37	0.727429
AI	1.21	0.827587
FDI	1.07	0.937943
Mean VIF	2.42	

C. Model Selection

This article uses the Hausman test to ultimately determine the selection of a fixed effects model. The results of the time individual dual fixed effects model are shown in Table 4 The innovation of artificial intelligence technology has a significant impact on the energy intensity of the manufacturing industry.

D. Mesomeric Effect Model

The Mesomeric effect three-step method is a commonly used analysis method of Mesomeric effect. As shown in Table 5, we first evaluate the direct effect. In equation (1), the direct effect of AI on lnEI is significant. Combining equations (2) and (3), it can be seen that IS has a significant impact on AI, and adding the intermediate variable IS enhances the impact of AI on lnEI. The same method combined with (4), (5) and (6), (7) can draw the conclusion that TFP1 and TFP2 have significant Mesomeric effect.

Table 4

lnEI	Coefficient	Std. err.	t	P>|t|	[95% conf. interval]
AI	-.0002462	.0000713	-3.45	0.001	-.000386 -.0001064
GDP	3.63e-06	2.24e-06	1.62	0.105	-7.63e-07 8.03e-06
FDI	-.0024959	.0006242	-4.00	0.000	-.0037196 -.0012722
TO	-9.00e-07	5.17e-07	-1.74	0.082	-1.91e-06 1.13e-07
Urb	-.0021991	.0037391	-0.59	0.556	-.0095289 .0051307
ECO	1.290971	.195368	6.61	0.000	.9079872 1.673954

Table 5

	(1)	(2)	(3)	(4)	(5)	(6)	(7)
Variable	lnEI	IS	lnEI	TFP1	lnEI	TFP2	lnEI
AI	-0.000246*** (-3.45)	-0.00293*** (-8.64)	-0.000254*** (-3.54)	0.000173*** (17.01)	-0.000316*** (-4.35)	0.0000933*** (9.71)	-0.000299*** (-4.18)
IS			-.0025284 (-0.99)				
TFP1					0.4073097*** (4.76)		
TFP2							0.5703542*** (6.31)
*** p<0.01, ** p<0.05, * p<0.1							

Table 6

	Observed coefficient	Bootstrap std. err.	z	P>|z|	Normal-based [95% conf. interval]
_bs_1	.0159663	.0016003	9.98	0.000	.0128298
_bs_2	.0450734	.0049997	9.02	0.000	.0352742

Table 7

	Observed coefficient	Bootstrap std. err.	z	P>|z|	Normal-based [95% conf. interval]
_bs_1	-.6554396	.0470805	-13.92	0.000	-.7477156
_bs_2	1.279375	.1855564	6.89	0.000	.9156915

Table 8

	Observed coefficient	Bootstrap std. err.	z	P>|z|	Normal-based [95% conf. interval]
_bs_1	-.6466107	.0525452	-12.31	0.000	-.7495973
_bs_2	2.758785	.2002056	13.78	0.000	2.366389

The Mesomeric effect three-step method is a relatively simple analysis method, which assumes that the relationship between variables is linear, and does not consider other possible common factors. Therefore, in actual research, this paper uses Bootstrap method to evaluate Mesomeric effect more comprehensively_ bs_ 1 Corresponding to the correlation coefficient of Mesomeric effect_ bs_ 2 corresponds to the correlation coefficient of the direct effect. From Table 6, Table 7, Table 8 we can see that industrial structure and Total factor productivity have a significant Mesomeric effect on the model.

E. Robustness testing

This article selects its lag model and random effects model for robustness testing, and the results are shown in Table 9. Artificial intelligence technology innovation has a significant negative correlation effect on manufacturing energy intensity, with some variables having a stronger impact on manufacturing energy intensity in random effects, indicating its mechanism of action.

F. Heterogeneity Analysis

According to the income level classification used by the World Bank in 2016, countries with per capita national income below $1045 are classified as low-income countries, countries with per capita national income between $1046 and $4045 are classified as low to middle-income countries, countries with per capita national income between $4046 and $12235 are classified as high to middle-income countries, and countries with per capita national income exceeding $12235 are classified as high income countries. Based on the 34 countries selected in this article, the division is shown in Table 10:

The data set covers almost all the major economies in the world, including the United States, China, Japan and Germany. Excluding some countries that have almost no AI patents, the remaining countries are divided into high-income countries and high-income countries, and the heterogeneity analysis is carried out on this basis. The specific regression results are shown in Table 11.

From the table, it can be seen that the impact of artificial intelligence technology innovation on manufacturing energy intensity in high to middle-income countries is significant at the 1% level, and the coefficient is negative. However, for high income countries, artificial intelligence technology innovation has no significant impact on manufacturing energy intensity.

Table 9

	(1) lnEI	(2) L.lnEI	(3) lnEI
AI	-0.000307*** (-4.21)	-0.000244*** (-3.30)	-0.000301*** (-4.27)
GDP	-0.00000557 (-1.92)	-0.00000236 (-0.75)	-0.0000316*** (-15.88)
FDI	-0.00199** (-3.15)	-0.000557 (-0.87)	-0.000985 (-1.57)
TO	-0.00000109* (-2.09)	-0.00000124* (-2.39)	-0.00000153*** (-4.89)
Urb	0.00303 (0.79)	-0.00447 (-1.06)	-0.0155*** (-4.81)
ECO	0.776*** (3.63)	1.132*** (4.76)	1.205*** (5.88)
IS	0.00574* (1.99)	-0.000172 (-0.06)	0.0240*** (9.41)
TFP1	0.134 (1.29)	0.127 (1.17)	0.519*** (5.28)
TFP2	0.583*** (4.82)	0.440*** (3.43)	1.120*** (10.10)
****** p<0.01, ** p<0.05, * p<0.1***			

Table 10

	Countries
High income countries	Australia, Austria、Belgium、Canada、Czech Republic, Denmark、Estonia, Finland、France、Germany, Greece, Hungary 、Ireland、Italy, Japan、Korea、Latvia、Lithuania、Norway、Poland、Portugal、Slovak Republic, Slovenia、Spain、Sweden、Switzerland、United Kingdom、United States
High to middle-income countries	Brazil、China (People's Republic of)、India、Indonesia、Mexico、Türkiye

Table 11

	(1) lnEI	(2) lnEI
AI	0.000156 (1.75)	-0.00164*** (-13.22)
GDP	-0.00000268 (-1.05)	0.000133*** (7.70)
FDI	-0.00216** (-3.26)	0.0178* (2.02)
TO	-0.00000123 (-1.94)	0.0000215*** (3.76)
Urb	-0.0366*** (-6.57)	0.0106 (1.12)
ECO	-0.274 (-0.84)	0.488 (1.24)
****** p<0.01, ** p<0.05, * p<0.1***		

V. CONCLUSION AND SUGGESTIONS

Through analysis of this article, it is found that innovation in artificial intelligence technology has a significant impact on the energy intensity of the manufacturing industry in middle-income and high-income countries. Improving innovation in artificial intelligence technology can reduce energy intensity in the manufacturing industry of middle and high-income countries. This article considers the practical application value and practical significance of the project from the following perspectives.

A. Practical Application Value

1) Adjust the Energy Intensity of the Manufacturing Industry to Save Economic Costs for Enterprises

Manufacturing enterprises optimize production equipment, reduce costs, improve standardized processes, and achieve optimal resource allocation through artificial intelligence technology innovation, thereby reducing energy consumption and improving production efficiency. Through artificial intelligence, products themselves can create more value for users, thereby driving product purchases, ultimately achieving the effect of reverse stimulation of the manufacturing industry and saving economic costs for enterprises.

2) Explore Innovative Directions and Fully Utilize Their Impact on the Development of the Manufacturing Industry

By deeply exploring the content of digital technology innovation, we can understand the specific impact path of artificial intelligence innovation on the energy intensity of the manufacturing industry. By adjusting the industrial structure and innovating in technology, we can reduce the energy intensity of the manufacturing industry, promote the development of artificial intelligence and green development of the manufacturing industry.

3) Bring Economic Benefits to Society and Contribute to National Economic Growth

AI technology innovation can build a more direct and efficient network and improve Economic efficiency. Promote the deep integration of artificial intelligence innovation and manufacturing industry, drive the transformation and upgrading of traditional industries, optimize industrial structure, lead the development of strategic emerging industries, achieve strategic adjustment of economic structure, and ultimately achieve national economic growth.

B. Realistic Significance

1) From the Perspective of Theoretical Expansion

This study, through empirical testing of survey data from manufacturing enterprises, can answer whether artificial intelligence innovation has reduced manufacturing energy intensity and its impact mechanism, filling the gap in research related to artificial intelligence innovation and enterprise energy consumption.

2) From the Perspective of Policy Practice

It conforms to the innovation driven development strategy and better implements the new development concept of innovation, coordination, green, openness, and sharing. This study is beneficial for the integration and development of artificial intelligence innovation and manufacturing enterprises, accelerating the transformation of economic development mode, promoting technological progress and innovation, and focusing on promoting green development. This provides certain reference value for the formulation and adjustment of policies related to the innovation and development of digital technology in the future, and the use of digital technology innovation to improve enterprise energy utilization efficiency.

3) From the Perspective of Economic Value

On the one hand, promoting the deep integration of artificial intelligence innovation and manufacturing, promoting the transformation and upgrading of industrial structure, reducing enterprise energy consumption, improving energy utilization efficiency, and saving economic costs are key measures to promote the high-quality development of China's manufacturing industry. On the other hand, it enhances social productivity and international competitiveness, allowing China to have an advantage in comprehensive energy utilization efficiency compared to different countries and regions, ushering in significant innovative development of digital technology in China, forming an international competitive advantage in the digital field, and playing a huge driving role in China's economic and social development.

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