Pol. J. Environ. Stud. Vol. 32, No. 6 (2023), 5425-5432
DOI: 10.15244/pjoes/169453 ONLINE PUBLICATION DATE: 2023-09-15

Original Research

Intelligent Effects and Green Development in China: Evidence from Energy-Growth Nexus

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Received: 16 May 2023
Accepted: 10 July2023

Abstract

Intelligence relieving energy consumption and economic growth nexus is important for green development. To explore the potential power for sustainability, this paper uses entropy weight method to measure the intelligent level, adopts decoupling indicator between energy consumption and economic growth for green growth performance, and builds a spatial model to diagnose the mechanism of decoupling system. The results show that the achievements of intelligent development in the three regions are remarkable, and the intelligent level in the eastern region is the most prominent of all. Regardless of regional differences, intelligence is the main and stable driver deepening decoupling indicator; Notable pushing-out or pushing-in spilling power on regional decoupling through many channels can be identified, namely urbanization, income and FDI. Clean energy can help promote the driving effects of intelligence on decoupling and is not confined by regions. The fierce green competition race in the form of "anti-typicality" mode exists in various regions, especially in the Western region; only in the Middle region, the intelligent spatial spillover effect can form the driving force for decoupling. Accelerating the intelligent development and the application of clean energy is an effective measure to achieve the green environmental targets.

Keywords: green development, intelligence, decoupling, adjusting effects, spillover

Introduction

In the past years, the rapid economic development in China has been accompanied with huge energy consumption, leading to the sharp increase in carbon dioxide emissions, which has put much pressure on green transformation and upgrading. The effective way for low-carbon production system construction requires that most of the remaining fossil resources should be kept underground. Since the promotion of energy production and consumption revolution firstly proposed, many policies and plans in energy consumption, energy supply, energy technology and system revolution followed. The Action Plan for Carbon Peak before 2030 also clearly proposes the guiding principle of "promoting economic and social development based on efficient energy utilization and low-carbon development". While, in the era of Industry 2.0, how to unleash the potential of sustainable low-carbon development depends on the use of information and communication technologies (ICT).

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The information revolution has largely changed the growth mode and continuously improved energy efficiency. Intelligent manufacturing creates the so-called “digital twins” by monitoring physical processes, using advanced information and manufacturing technologies, and makes intelligent decisions through real-time communication and cooperation with people, machines, sensors, etc. [1]. The enterprises can focus on energy-saving transformation, introduction of low-carbon intermediate products and investment in pollution control. Internet usage is playing an increasingly important role in fostering new dynamics of economic development, stimulating consumption, and enhancing innovation capacity [2]. As one of the countries with the most complete manufacturing system in the world, the number of used industrial robots in China has ranked first [3]. The cost reduction of technologies, robots and other things related to intelligent manufacturing can help obtain international competition instead of “demographic dividend” [4]. During the COVID-19, intelligent and digitization industries have become hot spots and are regarded as the source of comparative strengths in the new era. A series of policies have been issued, such as discount interest on technical transformation loans, relocation subsidies, employee resettlement subsidies, accelerated depreciation and investment by industrial guidance funds, encouraging enterprises to carry out digital transformation [5]. In April 2020, the “Implementation Plan for Promoting the Action of ‘Using Digital Wealth and Intelligence to Cloud’ to Cultivate New Economic Development” was released, to stimulate digital vitality, promote the integration of information, data, and intelligence, and achieve efficient operation. Can intelligent development attain economic growth and control energy consumption? What are the effects of intelligence on economic growth and energy consumption simultaneously? Whether intelligent development will be activated to achieve sustainable development, and how to stimulate the potential of intelligence, have become the key to solving environmental problems at present. So, around the above issues, the contributions of this article are as follows: construct a spatial model to sort out the exogenous spillover effects from the neighboring regions, measure the intelligent level in different regions to capture differences, discuss the direct eco-friendly benefits and economic gains of intelligent development by analyzing its impact on decoupling, and explore the eco-friendly path for sustainable development through improving intelligence.

This paper is organized as follows: Section 2, presents the literature review and theory hypothesis; Section 3 describes the variable selection, data source and constructs a spatial model; Section 4 analyzes the empirical results and makes some discussion, and Section 5 gives the specific conclusions and proposes some suggestions.

Literature Review

The extant research mainly discusses the economic and social welfare of intelligent development performance. Heckman et al. [6] and Hanson et al. [7] found that intelligent manufacturing significantly improved the financial and innovation performance of the enterprises, especially the economic growth; Mun et al. [8] found that the Internet has significantly improved the labor productivity and sales growth rate of manufacturing industry; Winroth [9] argued that the industrial output increased by 0.37% with the extensive use of robots in 17 countries. The vigorous development of intelligent manufacturing has incredibly promoted a large number of advanced business models and new industries, which in turn continuously injected fresh vitality into manufacturing industry [10]. Bai et al. [11] showed that the development of the digital economy has promoted economic efficiency but also transformed economic structures. As to social benefits, intelligent development brought much, such as employment and wages in the labor market. Intelligence creates the “destructive effect” on low skilled labor and the “creative effect” on high skilled labor [12], of which the knowledge, skills and creativity are the important sources to promote the technological innovation, value creation, energy conservation and emission reduction [13].

Environmental welfare of intelligence is usually indirectly discussed through exploring the additional gains from economic, social sides or directly through efficiency improvement and carbon reduction. Jabbour et al. [14] showed that with the automotive production and use of electronics and information technology, Industry 4.0 benefits environmentally-sustainable manufacturing and leans towards green products. Significant improvement in energy efficiency is also the result of intelligent development [15]. Higon D.A. [16] argued ICT is among the sources contributing to the increasing levels of CO_2 emissions in terms of production of ICT machinery and devices, energy consumption, and recycling of electronic waste. Especially, smart city construction significantly reduced per capita CO_2 emissions [17]. Li et al. [18] showed that The digital economy is of great significant for carbon emission reduction. Liu et al. [19] indicated that intelligent city construction can reduce carbon emissions by driving data elements agglomeration and optimizing industrial structure, and intelligent government and intelligent people’s livelihood policies can improve energy efficiency through green technological innovation. Most research focuses on the single positive environmental benefits brought by intelligent development or digital level, with little attention paid to both economic and environmental efficiency dividends. Decoupling, as an effective indicator to measure economic development and energy-saving benefits, has once again received attention in the 2030 Agenda for Sustainable Development. Decoupling between energy consumption and economic growth can be achieved due to technological progress, which has also been identified and regarded as results of environmental protection struggles in many countries, while fluctuates as the normal behavior [20-21]. The research tries to prove the feasibility of decoupling and explore the local driving factors and paths in an overall system. Neither the local spillover effect of the system nor the technical effect, income effect or direct impact on decoupling generated by intelligence are considered. No further research has been conducted on the direct impact or spillover effects of intelligence on both economic and energy efficiency. Based on this, this article mainly explores both of these from intelligent development and also try to identify the stimulating effect of regulatory factors.

Theoretical Hypothesis

The intelligent devices especially the perception and human-computer interaction based on human behavior imitation can more closely connect manufacturing nodes, and create efficient, innovative service network. Therefore, "Complementary effect" and "Substitution effect" bring more dividends than "Demographic dividend", improving production efficiency. The so-called production rebound is caused by the intelligent upgrading in the downstream enterprises, which has led to an increase in demand for intermediate products and raw materials by upstream enterprises. Through the collaborative progress of upstream and downstream processes, all production and market chains can be optimized. The ecological footprints, in most cases, reflect human economic activities which can be mediated by technology. Intelligent technologies can help manage production planning and scheduling, expand capacity utilization, and improve energy maintenance and supervision [22]. Intelligent manufacturing enables all physical processes and information flows to be available across the entire manufacturing supply chains, multiple industries, and can reduce energy consumption, which is conducive to the formation of low-carbon production mode to a certain extent [23]. At the same time, enterprises will employ more skilled labor under advanced intelligence level, who are inclined to use energy-saving technologies [24]. While, the initial stage of intelligent manufacturing inevitably allows enterprises to accumulate machine learning experience by running millions of statistical experiments, requiring high energy consumption [25]. Since renewable and clean energy doesn't cause carbon emissions, intelligent systems, industrial internet platforms, digital intelligent manufacturing, and cloud manufacturing can only better align with the current green theme when this energy is sufficient. Otherwise, the development of intelligence will also lead to an overall energy rebound. Clean energy can effectively alleviate the long-standing conflict between growth and the environment, and ensure energy demand in the information, digital, and intelligent economy.

Hypothesis 1: Intelligent development can promote decoupling between economic growth and energy consumption by improving economic efficiency and energy efficiency, and clean energy plays as a booster facilitating the driving effect.

The obvious "return benefit" in economic growth shows a wide range of spatial correlations and spillovers effects, which will be strengthened through the exchange of knowledge, technology and resource allocation [26]. Regional energy consumption correlates spatially and also constructs a spatial network though economic activities. With the help of information networks, the flow of digital information can accelerate communication between regions or enterprises in production supervision and energy monitoring, thereby producing better energy-saving effects. As high-quality labor shifts from region to region, or from one enterprise to another, especially the spillover of energy technology and other technologies, professional knowledge and technology also spill over [27]. Then, the bidirectional spatial network nodes of energy and economy are more closely connected.

Hypothesis 2: The decoupling effect between economic growth and energy consumption will spread between regions through direct or conductive channels, and intelligent development can deepen this spatial spillover effect.

Material and Methods

Variables Selection and Data Sources

Decoupling index (Dr) is calculated by the ratio of economic growth rate and energy consumption rate, using Tapio elastic index based on fixed-base period. The intelligent development index (int) consists of intelligent devices, intelligent technologies, and intelligent applications, measured using the entropy method. The total fixed assets investment of telecommunications is selected to represent intelligent devices, the number of software R&D personnel and the telecom income to represent the level of intelligent technology, and intelligent applications respectively. The system of decoupling is also influenced by economic structure, development level and technology inflow. The ratio of secondary industry to GDP (ind) is chosen for the industrial structure index, and per capita income(inc) used to measure the economic development level. To avoid the estimation bias, the lagged period is selected as a tool for income. The total amount of foreign direct investment (FDI), and the proportion of urban population (urb) are chosen to represent technological inflow and urbanization respectively. The power sector, which mainly relies on traditional thermal power generation, accounts for a large proportion of the total carbon emission sources. Therefore, the power sector is the main area that needs to replace fossil fuels with

Table 1. Descriptive Statistics of the Variables.

	Dr	int3	FDI	inc	ind	urb
Mean	0.702	0.0805	1191.248	22653.87	45.890	53.535
Maximum	1.978	0.736	19234.65	68033.62	61.5	89.6
Minimum	0.133	0.0000956	7	7990.15	16.54	26.87
Std. Dev.	0.303	0.0904	2055.429	10704.76	8.337	13.890
Unit			Million Dollar	Million Yuan	%	%
Observations	420	420	420	420	420	420

clean energy. The growth rate of power consumption is selected to represent clean energy (rew).

All data of China's 30 provinces (excluding Tibet) from 2005 to 2018 can be obtained from the China Information Industry Yearbook, the provincial statistical yearbook, the information network of the development research center of the State Council, etc. Table 1 shows the detailed information of variable data.

Method

To explore the influence of intelligence on decoupling, a common regression model, a spatial model and a spatial model with interactive terms are established. The general regression model with fixed individual and time effect is as follows:

$$Dr_{it} = c + \beta_1\, int_{it} + \sum \beta_k X_{it} + \lambda_i + \delta_t + \varepsilon_{it}$$

Where, *Dr* represents decoupling index, *int* for intelligence indicator, i and t denotes province and time respectively, X is independent variables matrix, and ε_{it} represents random disturbance term. A spatial model with fixed temporal-spatial effect is presented as follows:

$$Dr_{it} = \theta_1 w_{ij} Dr_{ijt} + \beta_1\, int_{it} + \theta_2 w_{ij}\, int_{it} + \sum \beta_k X_{it} + \sum \theta_m w X_{it} + \lambda_i + \delta_t + \varepsilon_{it}$$

Where, w_{ij} represents spatial weight matrix, $w_{ij} Dr_{ijt}$, $w_{ij}\, int_{ij}$, $w_{ij} X_{it}$ represent the variables matrix of spatial term.

The spatial model with interaction term built by XU et al. [28] is used to capture the adjusting effect of the regulatory variable. The equation is as follows:

$$Dr_{it} = \theta_1 w_{ij} Dr_{ijt} + \beta_1 \text{int}_{it} + \theta_2 w_{ij} \text{int}_{it} + \beta_2 R + \gamma \text{int}_{it} \times R + \sum \beta_k X_{it} + \sum \theta_m w X_{it} + \gamma w_{ij} \text{int}_{it} \times R + \lambda_i + \delta_t + \varepsilon_{it}$$

Where, R represents the regulator variable; λ_i denotes the fixed individual term, δ_t for the time fixed term.

Results and Discussion

Spatial Model Selection

As shown in Table 2, LM and RLM of spatial lag and spatial error are significant at the 1% level, indicating the rationality and effectiveness of the spatial models. LR test is performed to verify the temporal and spatial fixed effect, and the significant results justify the controlling effects. Results of Wald and Hausman test are significant at the 1% level, indicating that the null hypothesis that the Spatial Durbin model (SDM) can be simplified into a spatial lag or spatial error model is rejected.

Intelligence and Spatial Spillover Effects

The results of the two models presented in Table 3 are stable. The coefficients of int in both models are significantly negative, at the 5% level, indicating that the higher the level of intelligence is, the smaller the decoupling indicator will become, and the deeper the

Table 2. LM and RLM Tests.

Spatial	Statistics	Spatial	Statistics
LM (lag)	18.398 (0.0000)	LM (error)	11.568 (0.0010)
RLM (lag)	15.460 (0.0000)	RLM (error)	8.629 (0.0030)
LR (spatial-fixed)	793.556 (0.0000)	LR (time-fixed)	49.578 (0.0000)
Wald (lag)	42.343 (0.0000)	Wald (error)	49.405 (0.0000)
LR(Lag)	40.505 (0.0000)	LR (error)	46.3558 (0.0000)

decoupling degree will grow. Intelligent development, as a driving factor to the decoupling, is beneficial for green economy. However, the coefficient of the int spatial term is negative and insignificant, indicating that intelligence from the neighboring region can produce the push-in force to promote energy conservation in the local region if the spatial overflow channel is smooth. The eco-friendly effects brought by the intelligent development in the adjacent regions can spill out in the form of demonstration model in the local, and appear as catalysts in the decoupling system. However, the imbalance between the construction of Information infrastructure and the level of economic development, as well as the difference in the benefits of intelligent development, has greatly hindered the spillover effect between regions, which is exactly one of the main reasons why the spillover effect of intelligent development is not obvious. These verify the hypothesis1, but reject part of hypothesis 2, that is, intelligence can promote decoupling without spillover effects. In addition to the intelligent driving effects on the decoupling system, the decoupling force also comes from other regions,such as the "pushing in" force through other channels.

As shown in Table 3, the spatial term coefficient of the decoupling indicator is significantly negative, suggesting that the exogenous force in the decoupling system spilled from other regions is conducive to the energy consumption in the local. However, the “anti-demonstration” model, as a warning of the bad decoupling state in the adjacent region, reveals the competition of decoupling race in other regions. The implementation of energy-saving measures is constrained by industrial structure, regional resources and technological level. Some enterprises have moved high pollution departments to the areas with relatively loose environmental regulations and policies, leading to the well-known phenomenon of “pollution paradise” within the region. As to other factors, the coefficients of industrial structure and urbanization are significantly negative, indicating the driving effects on positive decoupling. Industrial structure upgrading is not only the performance of economic progress, but also the achievements of the new mode. The same is true for the construction of new urbanization, where the improvement of infrastructure and comprehensive coverage of public service facilities, as well as the significant improvement of the quality of public civilians, can greatly benefit the construction of a new economic system with high development and low energy consumption. While, the positive spatial term coefficients of the two variables indicate that the spillover effects from the elements of economic system in the neighboring regions form the dragging power on local decoupling, but can only be successfully transmitted through urbanization rather than industrial structure. The coefficient of income shows there is insignificantly positive impact on decoupling as the relationship between income and environment still hangs over the upward zone of EKC. And the significantly negative coefficient of income spatial term shows that the positive effects of income spilled from the neighboring is one source of the exogenous force. As known from Table 3, both the local FDI and its spillover effects forms a negative dragging power on decoupling. The inflow of foreign direct investment leads to economic growth and an increase in greater energy demand, which is a typical phenomenon of sacrificing the environment for economic growth.

Table 3. Regression Results of Models.

	Panel model	SDM	
	Panel-term	Panel-term	Spatial-term
int	-0.1680* (0.0846)	-0.1570* (0.0754)	-0.04434 (0.7941)
ind	-0.2204*** (0.0027)	-0.1618** (0.0121)	0.1540 (0.3094)
urb	-0.6049*** (0.0000)	-0.9387*** (0.0000)	0.6578** (0.0153)
inc	0.2824** (0.0313)	0.1704 (0.1489)	-1.3719*** (0.0000)
FDI	0.06842*** (0.0004)	0.0583*** (0.0005)	0.1213*** (0.0069)
ρ		-0.3330***(0.0000)	
Logl	434.8489	465.6534	
R2	0.9194	0.9321	
Individual-Temporal	Fixed		

*, **, *** represents tests significant at 10%, 5%, 1% level

Most of the driving factors are identified in the local decoupling system, and the push-in effects from the neighboring regions form the resistance force on local positive decoupling, showing that there is competition rather than cooperation among regions. Green development is unbalanced in the different regions, and the local regions compete as economic models instead of seeking coexistence. To explore the differences of force source on the positive decoupling, a further study on the decoupling system in the eastern, central and western regions will be done.

Regional Heterogeneity

The changing trace of intelligent level in the eastern, central and western regions during 2005-2018 has been presented in Fig. 1. Overall, the value of int in the eastern region is comparatively large, indicating there are remarkable achievements of intelligent development. As shown in Fig. 1a), the average annual growth rate of int in Guangdong, Jiangsu, Zhejiang and Fujian shows that intelligent level has increased significantly by 44%, 24%, 17% and 12% respectively. Guangdong, Jiangsu and Beijing in eastern region have higher intelligent level than other regions and have entered into the first

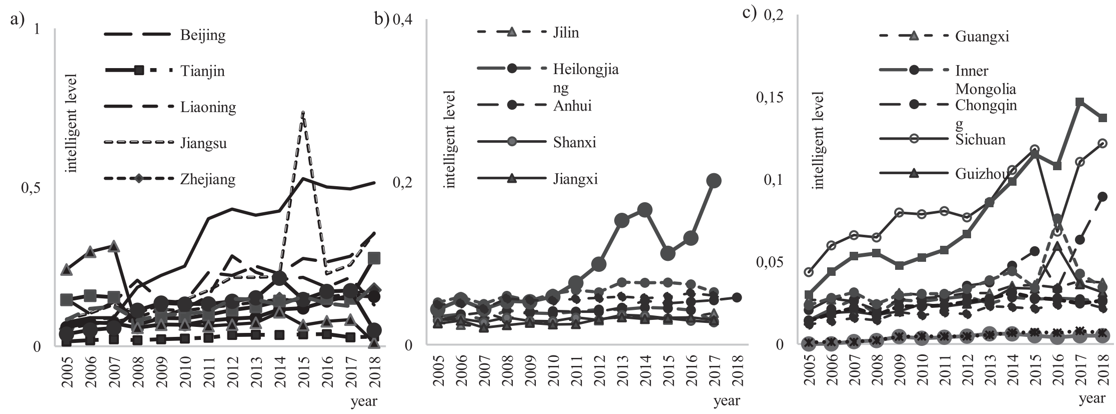

Fig. 1. Intelligent changing trace. a) intelligence in the east, b) intelligence in the middle, c) intelligence in the western.

echelon. However, Tianjin, Hainan in the last echelon have great potential in improving the intelligence level. As shown in Fig. 1b), The intelligent level in the central provinces has steadily improved slightly, and the intelligent indicator in Hubei is slightly higher than that in other provinces, indicating that it has become the leading position in the central region, and should continue to promote intelligent transformation to lay a good foundation for the intelligent empowerment in the central region. In Fig. 1c), intelligent indicators in Shaanxi and Sichuan increase by 27.3% and 13.7% respectively, a sign of excellent achievement. Chongqing, with an average annual growth rate of 25.5%, is also a region with good intelligent construction and has become a pioneer in the transformation of economic structure in the west. The differences in regional intelligent development are obvious, not only reflected in the development level, but also in the achievements of the new economic structure.

As shown in Table 4, compared to the whole, the coefficients of int in the three regions are robust and significantly negative at 1% level, indicating indicating that the driving force of intelligence on decoupling is stable and not limited to spatial differences. Intelligent development is an important thrust for the construction of the high-growth, low-consumption and low-emission economic system. The driving role of intelligence in the central and western regions is more prominent. Specifically, 1% increase in intelligent level will lead to 2.248% and 1.697% decrease in the decoupling index in the western region and central region, respectively. The spillover effects of the decoupling and its factors in the adjacent regions squeezes into the local region, merge as an external hindering force on the positive decoupling, and build "demonstration" model warning other regions. Except the insignificantly negative effect of intelligence on decoupling in the west and east, the intelligent development in the central region will spills, and become one of the exogenous positive drivers of local decoupling. There are certain advantages in transportation, science and education, such as the transportation capacity of the urban agglomeration in the middle reaches of the Yangtze River, and the relatively complete industrial chain layout formed by surrounding small and medium-sized cities, all of which are important reasons for the significant spillover effect of intelligence in the central region.

Table 4. Estimation Results of different regions.

Variables/ Regions	East	Middle	West
Int	-0.1535*** (0.00274)	-1.6970*** (0.0000)	-2.2479*** (0.0004)
W*Int	-0.1408 (0.1398)	-14.0152*** (0.0000)	1.2270 (0.3533)
ρ	-0.107** (0.0291)	-0.1289* (0.0957)	-0.670*** (0.0000)
LogL	287.910	177.519	179.344
R-squared	0.981	0.975	0.940

*, **, *** represents tests significant at 10%, 5%, 1% level

Adjusting Effects Test and Robustness Test

We construct a model with clean energy as the adjusting variable to further explore the adjusting effect in decoupling drive systems. As shown in Table 5, the coefficient of clean energy shows that spillover effects of clean energy from neighboring region can be a driver for local decoupling compared to the negative effects brought from the local one. The cross-term coefficient of clean energy and intelligent development is 1.722 and significant at the 5% level, indicating that clean energy will positively strengthen the intelligent driving effect on the positive decoupling. The corresponding spatial cross-term coefficient is 11.338, shows that the spillover effects brought by the wide use of clean energy in the other regions become the driving force facilitating intelligent pushing effects. Clean energy is helpful to inspiring eco-friendly benefits of intelligent development. To reduce carbon emissions, improving energy efficiency is a measure, and clean

Table 5. Interactive and Robust Testing Results.

	SDM (Int)		SDM (Int2)	
	Ordinary	Spatial	Ordinary	Spatial
Int	-0.2366** (0.015)	-0.2657 (0.1316)	-0.1802** (0.0183)	-0.1451 (0.2760)
IntRew	1.7216* (0.0742)	11.3376*** (0.0000)	1.2883* (0.0971)	8.6409*** (0.0000)
Rew	0.1523** (0.0410)	-0.5241*** (0.0071)	0.1676** (0.0197)	-0.431** (0.0213)
ρ	-0.3700*** (0.0000)		-0.3490*** (0.0000)	
Loglikelihood	483.8514		483.2319	
spatial -temporal	Fixed		Fixed	

*, **, *** represents tests significant at 10%, 5%, 1% level

energy plays an equal role in the transformation of energy structure.

The robustness test shown in the last two columns of Table 5 is relatively significant, indicating that the adjusting effects of clean energy and driving effects of intelligent development on decoupling are stable. The driving effects of intelligent development on decoupling is significantly positive, while insignificant and negative coefficient value of spatial term suggests the spilling channels have been hindered. The coefficients of interactive terms and spatial interactive terms consistent with the above-mentioned results suggest that the positive adjusting effects of clean energy can be identified not only from the local system but also the neighboring regions, which further demonstrates the robustness of adjusting force from clean energy.

Conclusions

To explore the ecological friendliness of intelligent development, this paper constructs a spatial model with interactive term to discuss the direct influence of intelligence on energy and economic efficiency, taking into account regional heterogeneity, correlation and adjusting factor. The conclusions and suggestions are as follows:

Firstly, intelligent development has facilitated decoupling, as well as the upgrading of industrial structure and urbanization. FDI and income levels are factors that trigger adverse changes or even positive decoupling instability. One driving factor for decoupling is the spatial self overflow effect, which is not constrained by regional differences. Each region competes with each other in the green transformation competition, with one retreating and the other forwarding. However, due to the limited transmission caused by regional disparities, the spillover effects of certain driving factors are not significant. In summary, the intelligent development of these three regions has shown stable ecological benefits. It is urgent to strengthen intelligent development and tap into the potential for decoupling. Narrow intelligent gap among regions, stimulate the driving force of intelligence, collaborate to build a platform for data and information flow, and fully leverage the green benefits of intelligent industry.

Secondly, the level of intelligent development in the western, central, and eastern regions has significantly improved, but the gap is evident, with prominent regional heterogeneity. Compared with the other two, the intelligence level in the eastern region is relatively high, with obvious front-line advantages; In the central and western regions, there is still great potential for intelligent improvement. Compared to the other two, only in the western region, green benefits of intelligent development can be spilled across the region and form as a driving factor pushing positive decoupling. Improve the intelligent level in the eastern region, narrow the intelligent gap between the lagged and the leading provinces, tap the eco-friendly potential of intelligence, and promote high-quality economic transformation.

In addition, clean energy can enhance the ecological friendly benefits of intelligent development and greatly enhance the driving role of intelligence in decoupling. The development of clean energy is a symbol of consolidating the foundation of intelligent applications, and also an effective assistance in solving environmental problems and achieving low-carbon emissions in the era of data economy. It is efficient to push the intelligent transformation of industry, accelerate for the realization of sustainable development with excellent economy and ecological environment by promoting the intelligent construction of clean energy sector, accelerating the transformation of smart energy, reducing the cost of energy application, and building an energy kinetic pool for industrial upgrading.

Acknowledgments

This work was funded by natural Science Foundation Project of Fujian (Grant No. 2021J05269); the Innovation Strategy Research Project of Fujian Province, China (Grant No. 2023R0075). National Statistical Science Research Project of China (Grant No. 2021LY100); Key Project of Philosophy and Social Science Planning of Zhejiang Province (Grant No. 23NDJC055Z).

Conflicts of Interest

The authors declare that they have no competing interests.

References

1. SHEN W.M., NORRIE D.H. Agent-based systems for intelligent manufacturing: a state-of-the-art survey. Knowledge & Information Systems, **1** (2), 129, **1999**.
2. BAI W.T., HOU J., XU J.J., CHEN J.C. Does digital economy development successfully drive the quality of green innovation in China? Polish journal of Environmental Studies, **32** (3), 2001, **2023**.
3. CHENG H., JIA R., LI D., LI H. The Rise of Robots in China. Journal of Economic Perspectives. **33 (**2), 71, **2019**.
4. GRAETZ G., MICHAEAL G. Robots at Work.The Review of Economics and Statistics, **100** (5), 753, **2015**.
5. LIN D.P., LEE C.K.M., LAU H.,YANG Y. Strategic response to industry 4.0: an empirical investigation on the Chinese automotive industry. Industrial Management & Data Systems, **118** (5), **2018**.
6. HECKMAN J.J., HIDEHIKO I., TODD P.E. Matching as an econometric evaluation estimator: evidence from evaluating a job training programme. Review of Economic Studies, **4**, 4, **1997**.
7. HANSON R. Economic growth given machine intelligence. Journal of Artificial Intelligence Research,**11**, 13, **2000**.
8. MUN S.B., CHUN H., CHO J. The effects of internet use on productivity and growth at the firm level-International Telecommunications Policy Review, **21** (3), 53, **2014**.
9. WINROTH A. Robots at work. Mechanical Engineering, **138** (10), 8, **2016**.
10. MULLER J.M., BULIGA O., VOIGT K.L. Fortune Favors the Prepared: How SMEs Approach Business Model Innovations in Industry 4.0. Technological Forecasting and Social Change, **132**, 17, **2018**.
11. BAI W., HOU J., XU J., CHEN J. Does Digital Economy Development Successfully Drive the Quality of Green Innovation in China?, Polish Journal of Environmental Studies, **32** (3), 2001, **2023**.
12. AGHION P., JONES B.F., JONES C.I. Artificial Intelligence and Economic Growth. National Bureau of Economic Research, **2018**.
13. GARDAS B.B., MANGLA S.K., RAUT R.D., NARKHEDE B., LUTHRA S. Green talent management to unlock sustainability in the oil and gas sector. Journal of Cleaner Production, **229**, 850, **2019**.
14. JABBOUR A.B., JABBOUR C.J.C, FOROPON C., FILJO M.G. When Titans Meet- Can Industry 4.0 Revolutionize the Environmentally-sustainable Manufacturing Wave? The Role of Critical Success Factors. Technological Forecasting and Social Change, **132**, 18, **2018**.
15. MACHADO C.G., WINROTH M.P., SILVA E..H. Sustainable manufacturing in Industry 4.0: an emerging research agenda. International Journal of Production Research, **58** (5), 1462, **2020**.
16. PAPAPIANNIDIS S., MARIKYAN D. ICT and environmental sustainability: A global perspective. International Journal of information Management, **63**, 102445, **2022**.
17. GUO Q.B., WANG Y., DONG X.B. Effects of smart city construction on energy saving and CO2 emission reduction: Evidence from China. Applied Energy, **313** (6), 118879, **2022**.
18. LI Z.G., WANG J. The Dynamic Impact of Digital Economy on Carbon Emission Reduction: Evidence City-level Empirical Data in China. Journal of Cleaner Production, **351**, 131570, **2022**.
19. LIU X.M., ZHANG Y.Q. Study on the impact of intelligent city pilot on green and low-carbon development. Environmental Science Pollution Research. **30**, 57882, **2023**.
20. WU Y., ZHU Q.W., ZHU B.Z. Comparisons of Decoupling Trends of Global Economic Growth and Energy Consumption between Developed and Developing countries. Energy Policy, **116**, 30, **2018**.
21. KULIONIS V., WOOD R. Explaining decoupling in high income countries: A structural decomposition analysis of the change in energy footprint from 1970 to 2009. Energy, **194**, 823, **2020**.
22. SZALAVETZ A. Industry 4.0 And Capability Development in Manufacturing Subsidiaries. Technological Forecasting and Social Change, **145**, 384, **2019**.
23. WAN J.F., TANG S.L., LI D., WANG S.Y. A manufacturing big data solution for active preventive maintenance. IEEE Trans Ind Inform. **13** (4), 2039, **2017**.
24. MACHADO C.G., WINROTH M.P, SILVA E. Sustainable manufacturing in Industry 4.0: an emerging research agenda. International Journal of Production Research, **58** (5), 1462, **2020**.
25. ZHOU S.J., SHAN F.X. Discovery of innovation effect and spillover effect: Evidence from intelligent manufacturing promoting low-carbon development, Journal of innovation & knowledge, **8** (3), **2023**.
26. OVERMAN H.G., RICE P., VENABLES A.J. Economic linkages across space. Regional Studies, **44** (1), 17, **2010**.
27. HERRERIAS M.J., CUADROS A., LUO D. Foreign versus indigenous innovation and energy intensity: further research across Chinese regions. Applied Energy, **162** (15), 1374, **2016**.
28. XU H.L., DENG Y.P. Does foreign direct investment cause environmental pollution in China-Research on spatial meteorology based on China's inter provincial panel data. Management world, **2**, 14, **2012**.