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# Improving the efficiency of China's energy sector based on Industry 4.0 principles

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***Abstract. Purpose.*** *The purpose of the article is to investigate the impact of Industry 4.0 principles on enhancing the efficiency of China's energy sector amid the global economic transformation.* ***Methods.*** *The study employs a systematic approach, comparative analysis, statistical data processing, and case study methods to examine the practical application of digital technologies in the energy sector.* ***Results.*** *Particular attention is given to the analysis of key Industry 4.0 technologies such as the Internet of Things (IoT), Artificial Intelligence (AI), Big Data, Digital Twins, Smart Grids, and automated control systems. It is substantiated that the implementation of these technologies contributes to the modernization of energy infrastructure, resource consumption optimization, carbon emission reduction, and increased energy supply stability. A comparative analysis of the development dynamics of China's energy sector over the past 10 years is conducted, identifying major trends and challenges. In particular, the transition of the country's energy structure toward a higher share of renewable energy sources, the development of energy storage systems, and digital monitoring platforms is highlighted. Practical cases of implementing innovative Industry 4.0-based solutions across different regions of China are presented, demonstrating increased efficiency in energy generation and distribution.* ***Conclusions.*** *The study concludes that the digital transformation of the energy sector is a key factor in ensuring energy security, environmental sustainability, and the sustainable development of China's economy.*

*The obtained results can be used to develop energy strategies in other countries seeking to integrate Industry 4.0 principles into their national energy systems.*

***Keywords:*** *national economy, resource support of international activity, insurance of international activity, economic diplomacy, international trade, energy efficiency, smart energy systems, economic analysis of international business, risk.*

## Підвищення ефективності енергетичного сектору Китаю на основі принципів Індустрії 4.0

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***Анотація. Метою статті*** *є дослідження впливу принципів Індустрії 4.0 на підвищення ефективності енергетичного сектору Китаю в умовах глобальної трансформації економіки.* ***Методи.*** *У дослідженні використано системний підхід, методи порівняльного аналізу, статистичної обробки даних, а також кейс-стаді для вивчення практичного застосування цифрових технологій в енергетиці.* ***Результати.*** *Особлива увага приділяється аналізу ключових технологій Індустрії 4.0, таких як Інтернет речей (IoT), штучний інтелект (AI), великі дані (Big Data), цифрові двійники (Digital Twins), смарт-мережі (Smart Grids) та автоматизовані системи управління. Обґрунтовано, що впровадження цих технологій сприяє модернізації енергетичної інфраструктури, оптимізації споживання ресурсів, зниженню викидів вуглецю та підвищенню стабільності енергопостачання. У роботі проведено порівняльний аналіз динаміки розвитку енергетичного сектору Китаю за останні 10 років, виявлено основні тренди та виклики. Зокрема, окреслено зміну енергетичної структури країни в бік збільшення частки відновлюваних джерел енергії, розвиток систем зберігання енергії та цифрових платформ моніторингу. Висвітлено практичні кейси впровадження інноваційних рішень на основі Індустрії 4.0 у різних регіонах Китаю, що демонструють зростання ефективності генерації та розподілу енергії.* ***Висновки.*** *Зроблено висновок, що цифрова трансформація енергетичного сектору є ключовим чинником забезпечення енергетичної безпеки, екологічної стійкості та сталого розвитку економіки Китаю. Отримані результати можуть бути використані для формування стратегій розвитку енергетики в інших країнах,*

*що прагнуть інтегрувати принципи Індустрії 4.0 у національні енергетичні системи.*

***Ключові слова:*** *національна економіка, ресурсне забезпечення міжнародної діяльності, страхування міжнародної діяльності, економічна дипломатія, міжнародна торгівля, розумні енергосистеми, економічний аналіз міжнародного бізнесу, ризики.*

**Problem Statement.** The global energy landscape is undergoing a fundamental transformation driven by the principles of Industry 4.0, which include digitalization, automation, artificial intelligence (AI), and the Internet of Things (IoT). As one of the world's largest energy producers and consumers, China faces pressing challenges in balancing its rapid industrial growth with environmental sustainability and energy efficiency. Despite significant investments in renewable energy and grid modernization, China's energy sector continues to encounter problems related to overcapacity in traditional sources, inefficient energy use, regional disparities in energy distribution, and high levels of carbon emissions.

The energy system in China is characterized by complex interdependencies between industrial development, energy demand, and technological innovation. While the country has adopted several strategic plans, including the "Made in China 2025" and the "Dual Carbon" goals, the integration of smart technologies into energy infrastructure remains uneven and underutilized. Additionally, legacy systems and regional imbalances further complicate the implementation of advanced technological solutions.

Given the urgency to meet climate targets and ensure long-term energy security, the application of Industry 4.0 technologies such as AI-based predictive analytics, intelligent sensors, blockchain for energy trading, and smart grids can significantly improve operational efficiency, reduce waste, and enable better decision-making in real time. However, systematic and data-driven assessments of their impact in the Chinese context are still limited.

Therefore, it is essential to investigate how Industry 4.0 can be effectively applied to China's energy sector, identify the key technological enablers, evaluate their economic and environmental benefits, and explore strategies to overcome existing barriers to implementation. This study aims to bridge this gap by presenting a comprehensive analysis of the role of Industry 4.0 in transforming the energy landscape of China.

**Analysis of recent research and publications.** Recent studies have extensively examined the influence of Industry 4.0 technologies on China's energy sector, yielding a spectrum of findings. While some research underscores the positive impact of digitalization on energy efficiency, others highlight the complexities and potential limitations of such technological integrations. For instance, Rong et al. (2024) conducted an empirical study revealing that a 1% increase in industrial intelligence correlates with a 0.121% rise in total factor energy productivity (TFEP) in the studied area [12]. This effect is further amplified by factors like environmental regulation, industrial upgrading, and advanced human capital. Similarly, Jia et al. (2024) found that regional digitalization significantly enhances energy efficiency in China's industrial enterprises [13]. Their study emphasizes that technological innovation and supportive policies, such as the "National Innovative Pilot Cities" initiative, bolster this positive impact. Conversely, research by the Research Institute for Sustainability (RIFS) indicates no significant link between Industry 4.0 adoption and reductions in energy consumption or intensity across ten Chinese manufacturing sectors from 2006 to 2019. The study suggests that digitalization alone may not automatically lead to anticipated energy savings in manufacturing and industry. Further complicating the narrative, a study published in Renewable and Sustainable Energy Reviews highlights that while digitalization in manufacturing is expected to improve energy efficiency, it may also lead to increased energy consumption due to growth-inducing effects and outsourcing of energy-intensive tasks. This underscores the need for policymakers

to focus on reducing absolute energy consumption rather than solely targeting energy intensity metrics.

In the realm of renewable energy, China's commitment is evident. As reported by the Financial Times, China achieved its 2030 goal of 1,200 gigawatts of installed solar and wind capacity six years ahead of schedule. This rapid advancement is part of a broader strategy to modernize the power grid and reduce carbon emissions, despite challenges posed by the dominance of state-owned coal industry groups. Moreover, a study by Shi (2022) emphasizes the dual nature of intelligent energy development. While the production of energy equipment can cause environmental pollution, the deployment of intelligent energy systems ensures stability in energy supply and reduces environmental impact, highlighting the importance of sustainable practices in the energy sector. Collectively, these studies illustrate the multifaceted impact of Industry 4.0 technologies on China's energy sector. While digitalization and smart technologies offer promising avenues for enhancing energy efficiency, their effectiveness is contingent upon supportive policies, technological innovation, and sustainable practices.

The authors' contribution lies in the comprehensive assessment of Industry 4.0 technologies and their transformative impact on China's energy sector. They conducted a comparative analysis of the sector's development over the past decade, highlighting trends such as the shift toward renewables, digitalization, and improved energy efficiency. Their findings offer practical insights and strategic guidelines for applying Industry 4.0 solutions to modernize energy systems globally.

**The aim of the article** is to assess the potential and practical application of Industry 4.0 technologies for enhancing the energy efficiency and sustainability of China's energy sector, with a focus on identifying challenges, opportunities, and policy recommendations.

**Presentation of the main research material.** The Fourth Industrial Revolution is what Industrial Revolution 4.0 denotes, and it marks the achievement

of manufacturing industries towards intelligence, networking, and digitalization development. A very important mission has been assigned to Industry 4.0 for the human industrial industry development.

As shown in the article by Khan, I. H., & Javaid, M., titled “Industrial Applications of Internet of Things: A Systematic Review”, the authors argue the Internet of Things (IoT) is an important part of Industry 4.0 [1]. It has a wide range of applications in the monitoring of production systems in the manufacturing and service industries. This technology opens new possibilities for innovation in the manufacturing industry by improving performance. The main function of IoT is to collect and share information with the help of machines and devices connected to the Internet [1, 7-8]. It is associated with a unique identification number or code and can be controlled through everyday devices such as smartphones. The main components of this technology are software, hardware, and network connectivity for data exchange and collection.

These achievements are the result of digital transformation. Digital technology combines power energy supply with actual use issues to achieve higher efficiency and change residents' living efficiency in a more convenient and quick way. This is also the result of digital transformation of enterprises, which enables residents to understand electricity consumption more quickly and conveniently, to adjust electricity consumption more quickly, which can help residents reduce costs and bring a good image to enterprises.

Through digital transformation, we can develop differentiated energy supply methods for different types of users. We can collect user usage habits, including electricity usage time and electricity demand, through smart meters and other devices, analyze and give different electricity usage strategies, especially staggered electricity consumption. In China, electricity prices are different in different time periods. In 2025, Wang Chen mentioned in the "Monthly China Energy Update" [2, 9] that the peak hours are 10:00-12:00 and 15:00-21:00, and the trough hours are

23:00-07:00 the next day. The price per kilowatt-hour is about 3 to 4 times different. By the end of 2024, China's total electricity consumption will be close to 1 trillion kWh, a year-on-year increase of 6.8%, higher than the GDP growth rate of about 5% in 2024. This is due to the overall improvement of the electrification level of the primary industry (year-on-year growth of 6.3%), the tertiary industry (year-on-year growth of 9.9%), and urban and rural residents' lives (year-on-year growth of 10.6%).

With the help of digital technology, energy equipment can achieve intelligent transformation. The digital economy also promotes and optimizes the energy supply chain. Faced with China's huge investment in the transformation of the energy industry, a reasonable optimization method is to establish digital supply chain management, share information with suppliers and customers, and show efficiency in real time. Enterprises can better coordinate the production and use of energy and resources, reduce transportation costs, and improve energy utilization. Digital transformation can also play a huge role in different links in different energy fields, promoting the sustainable development of the energy industry through data-driven and smart grid construction, production automation, and energy consumption optimization.

In the current era of Industry 4.0, various digital technologies play a very important role in deeply affecting the improvement of energy efficiency, including the interaction between the Internet of Things and smart sensors, the use of big data and artificial intelligence, and blockchain technology. The main role of artificial intelligence technology in digital transformation is to use analytical data and realize energy prediction, and to find abnormal problems, and then optimize the entire process, to minimize the waste of resources. Blockchain technology is mainly used to improve the transparency of energy transactions through distributed ledger technology, which not only reduces transaction costs, but also makes transactions more convenient.

However, China's energy efficiency is currently stable but also has an upward trend, which shows that China's current energy development direction is correct (Fig. 1).

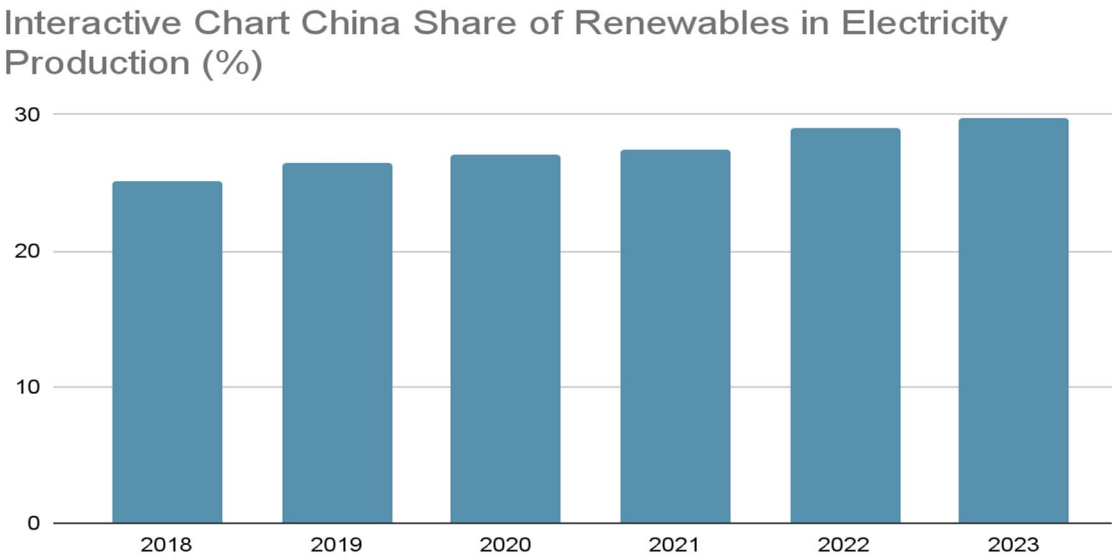


**Figure 1.** China's renewable energy generation share (Annual data of rural China from 2018 to 2023）

*Source：China energy information [3]*

In the (Figure 1) of the proportion of renewable energy in China's electricity production process, the total proportion increased by 3.88% from 2018 to 2023. In 2018, China's National Development and Reform Commission also set a goal of 9% non-hydropower renewable energy in electricity consumption in 2020 and 35% in 2030 (15% in 2023). This is about career planning after Industry 4.0, but the overall trend is greatly improved. After analysis, the main reason is that Industry 4.0 has added automation and intelligence. In the process of electricity production, sensors can obtain data more accurately with the help of the Internet of Things, and wind direction and temperature can also adjust different parameters, which can improve the efficiency of the production process by 10%-15%. The intelligent system

allocates energy data according to real-time demand, greatly improving the efficiency of different energy distribution areas.

In terms of energy advancement, China's promotion of independent decision-making on energy equipment is mainly based on the independent formulation of energy strategies, with the main purpose of reducing human intervention. According to author Roberts, M in Carbon Brief: China, China's key indicator forecast for 2030 is that the penetration rate of intelligent equipment will reach 80%, and the proportion of digital-driven decision-making will reach 70% [4, 10, 11]. For the industrial Internet platform, the data of the entire industry will be integrated to achieve cross-regional and cross-energy intelligent scheduling. In fact, it is to build an energy brain to achieve the functional complementarity between electricity, heat and gas to achieve the "dual carbon" goal. The sharing rate of production and sales within Chinese energy enterprises is only 55%, and compound talents who understand the energy engineering industry and the industrial Internet only account for 12% of the technical industry. In addition, the cost of digital transformation of old equipment (machines invested before 2010) is high, and the interconnection rate between systems is less than 40%. There is a lot of room for improvement in the digitization and automation of China's energy industry. Only 60% of enterprises have professional industrial control safety protection systems, so China's current automation level belongs to step-by-step, as stable as possible, to avoid the negative impact of high-speed development.

China is the world's largest energy consumer. Many well-known companies have set up factories in China. China is also famous for its manufacturing industry. Naturally, its energy consumption is also huge. China's energy output mainly relies on fossil energy, and coal accounts for more than 50% of it. Therefore, one of China's goals is the "dual carbon" goal. Therefore, China's new energy technology has begun to develop, but the intermittent and volatile nature of it is challenging. At present, China's energy system is not efficient, the consumption of traditional power

transmission is very high, and it is difficult to access distributed energy. In addition, China's industrial and construction industries have unreasonable energy distribution, which is a serious waste. This requires the use of IoT equipment technology to optimize energy equipment. Therefore, the Chinese government has proposed a strategic plan for new energy power systems and energy Internet to promote the integration and development of energy and technology.

Currently, China's digital economy and automation are in a stage of rapid development. The Chinese government has also proposed the "14th Five-Year Plan" for the development of the digital economy. According to the National People's Congress, (2021), "The 14th Five-Year Plan sets out China's development strategy and path for 2021-2025, and puts forward specific environmental and efficiency goals. Like the previous five-year plans, the 14th Five-Year Plan also plans the direction of China's climate action for 2021-2025, and mentions the long-term direction of action before 2035. The plan was issued and approved by the National People's Congress in March 2021. The plan reiterates the previously announced goal of achieving carbon neutrality by 2060 and sets a goal of peaking emissions by 2030" [5, 11]. China's "14th Five-Year Plan" focuses on the development of cloud computing, big data, blockchain, 6G, industrial Internet, etc., with the main goal of building an independent and controllable digital technology industry chain.

In 2024, 38% of China’s electricity will come from low-carbon energy, slightly lower than the global average of 41%, making it the country with the largest electricity demand in the world. In the article ‘China accounted for more than half of the global increase in wind and solar power in 2024, the author Ember mentioned that hydropower is China’s largest source of clean electricity, accounting for 13% in 2024. Wind and solar power together account for 18%, slightly higher than the global average of 15%, and higher than neighboring Asian countries Japan (11%) and South Korea (6%) [6]. In 2024, China will account for half of the world’s electricity generation, and its energy production is growing rapidly. As the world’s

largest electricity consumer market, China’s total electricity demand is expected to reach one-third of the world’s total electricity demand that year, and more than 80% of the new electricity demand will be met by clean energy.

China's electricity consumption as a percentage of total energy continues to grow, with data centers, cloud computing and all new energy sectors all using more than 30%. The convergence model of smart grids has promoted the diversification and development enthusiasm of the energy industry. The deeper challenge is that the transformation of the traditional energy structure requires a lot of talent and capital investment. In the field of artificial intelligence and wind power generation, since artificial intelligence can monitor weather and energy storage space in real time, it can adjust data status in time, increase power generation by 10%-15%, and reduce manual intervention by 70%.

If small and medium-sized enterprises want to transform digitally, it will cost tens of millions of dollars to build a smart substation, and there will be no obvious benefits in the short term. In addition, there is a huge talent gap, with 40% of positions lacking suitable talents. On the other hand, the government must set up a digitalization fund specifically for small and medium-sized enterprises to bear half of the transformation costs.

The unique concepts and key technologies of Industry 4.0 in the energy sector include the Internet of Things, artificial intelligence, and the integration of the Internet of Things, big data analysis, and artificial intelligence. The integration of these technologies is changing the production and consumption patterns of the energy industry. The deep integration of all aspects of the Internet of Things, big data analysis, artificial intelligence, and cloud computing, as well as the construction of different innovative models for intelligent development in the energy sector.

**Conclusions.** This study has highlighted the growing significance of Industry 4.0 technologies in optimizing China’s energy sector. It was demonstrated that smart grids, AI-driven systems, and the IoT can drastically improve energy distribution,

consumption monitoring, and the integration of renewables. By comparing current energy practices with the transformative capabilities of digital tools, the research confirms that the digital transformation of China's energy sector is essential for achieving carbon neutrality and long-term sustainability. The article also emphasized the importance of addressing regional disparities and upgrading existing infrastructure to unlock the full potential of Industry 4.0. To achieve this, strategic investments, public-private partnerships, and supportive regulatory frameworks are critical. Furthermore, the development of human capital and technical expertise will play a decisive role in implementing intelligent energy solutions on a national scale. In conclusion, the study confirms that applying Industry 4.0 principles to China's energy sector offers a viable pathway to increased efficiency, reduced emissions, and improved energy security. However, achieving these outcomes requires coordinated efforts across all levels of governance and industry to overcome technological and institutional barriers.

The impact of Industry 4.0 is enormous, and its impact on technology, the environment, and the economy is even more far-reaching. It not only benefits energy companies in cost savings and improved competitiveness, but also provides scientific examples and solutions for other similar companies around the world, jointly promoting the development of global Industry 4.0 and giving full play to the concepts and methods of Industry 4.0 in the energy industry, as well as its advantages in the energy field. Through a systematic study of Industry 4.0, we recognize its positive role in promoting changes in the energy industry, improving energy efficiency, and achieving national sustainable development goals. In the future, with the continuous innovation and progress of Industry 4.0, we will continue to improve evaluation methods and theories, optimize strategies and application models in different scenarios, and provide more specific and targeted guidance for the intelligentization, digital transformation, and high-quality development of the energy industry.

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