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Original Paper

The impact of industrial transformation on green economic efficiency: New evidence based on energy use

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A B S T R A C T

Developing a green economy is key to achieving the 2030 Sustainable Development Goals. This paper uses the SBM-GML index, which includes non-desired outputs, to measure the trend of regional green economic efficiency changes and analyze the impact mechanism and realization path of industrial transformation on green economic efficiency. The research results show that advanced industrial structure has a positive influence on green economic efficiency nationwide, while energy utilization structure and energy utilization efficiency have positive partial intermediary effects in the influence path; industrial structure rationalization is also significantly positively related to green economic efficiency nationwide, and the mediating effect of energy utilization is positive. The impact of industrial transformation on green economic efficiency has regional heterogeneity, and the mediating effect of energy use also differs. Among them, the impact effect in the eastern region is basically consistent with the national sample, but is negative in the central and western regions. This paper proposes countermeasures in terms of adjusting the industrial structure, improving energy efficiency, and perfecting industrial and energy policies, which can provide theoretical and practical references for promoting the transformation and upgrading of regional industrial structure, optimizing energy utilization, and advancing the efficiency of the national and regional green economy.
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1. Introduction

The 70th session of the United Nations General Assembly adopted Transforming Our World: The 2030 Agenda for Sustainable Development, which identifies 17 goals and 169 targets for achieving sustainable development (Terama et al., 2016; The United Nations, 2020). It covers the economic, social, and ecological aspects of sustainable development. In the same year, parties including the United States, France, the United Kingdom, Germany, and China jointly reached the Paris Climate Change Agreement to address climate change and promote sustainable development as a global adaptation goal. The United Nations released the Green Economy Report which considers the green economy as an important strategic choice to achieve global sustainable development (United Nations Environment Programme, 2011). The IPCC report Climate Change 2022: Mitigating Climate Change identifies a continuing need to further increase global awareness of the urgency of mitigating climate change. As a new economic form, the green economy pursues “economy to be environmentally friendly, environmental protection to be economic”, trying to create wealth growth in the harmonious coexistence of man and nature. The green economy and its related green growth, green recovery, green new deal, and green revolution have currently become an important tool for the restructuring of the world economy and global environmental governance (Borel-Saladin and Turok, 2013; Smit and Musango, 2015; Patel and Goodman, 2020; Zhou et al., 2022; Moore and Koski-Karell, 2023). With the deepening of multipolarization and economic globalization in the world, China's ties with the world have become increasingly close. Green development is an important part of China's new development philosophy. China has actively participated in global environmental governance and responded positively to global climate change, becoming an important participant, contributor and leader in the construction of a global ecological civilization. China has proposed to reach peak

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carbon dioxide emissions by 2030, striving to achieve carbon neutrality by 2060, and integrating dual-carbon targets into the overall layout of economic and social development and ecological civilization construction. The dual carbon goal is an important hand in leading green and low-carbon development, and is of far-reaching significance in promoting a Chinese-style modernization in which human beings coexist harmoniously with nature. In October 2021, the State Council of China issued the “Action Program on Carbon Peak by 2030” to ensure the implementation of the dual carbon strategy, which explicitly proposes the full implementation of energy green and low-carbon transformation actions. In March 2022, China's National Development and Reform Commission and the National Energy Administration issued the Modern Energy System Plan for the 14th Five-Year Plan, which set different targets for energy security, low-carbon energy transformation, energy efficiency and energy structure, etc. In 2023, China's National Energy Administration issued the Guiding Opinions on Energy Work in 2023, which explicitly pointed out the need to focus on growing the clean energy industry, speeding up the promotion of a green transformation of the development mode, and further promoting the development of energy in a safer, greener and more efficient manner (Zhang et al., 2013; Cui et al., 2019; Hepburn et al., 2021; Ren et al., 2022; Fang et al., 2023; Wang and Liao, 2023). The total annual energy consumption increased by 2.9% over the previous year, coal consumption increased by 4.3%, comprehensive energy consumption per unit of calcium carbide by energy-consuming industrial enterprises decreased by 1.6%, and national energy consumption per 10,000 yuan of GDP decreased by 0.1% over the previous year in 2022 (National Bureau of Statistics, 2023), indicating that industrial structure transformation and energy use improvement has a significant influence on enhancing regional green economic efficiency and sustainable development.

The structural dividend hypothesis suggests that the cross-sectoral reallocation of factors of production, that is, the flow of factors of production from inefficient to efficient sectors, can effectively improve production efficiency, and this process plays an important role in the process of economic growth (Furieri et al., 2012; Gan et al., 2013; Drummond and Ekins, 2017; Li et al., 2020; Zhang et al., 2022; Yang et al., 2023). The direction and effect of industrial structure on green economic efficiency are various in the previous research results (Hao et al., 2022; Lu et al., 2022; Mealy and Teytelboym, 2023). On the one hand, industrial transformation and upgrading have brought about the research and development and application of green and low-carbon technologies. The transformation of dynamic energy can help accelerate the elimination of backward technologies, processes, equipment and production capacity in heavily polluting industries, comprehensively promote energy-saving and efficiency strategies, and promote green production methods (Li, 2023; Zhao et al., 2023; Zhong et al., 2023). On the other hand, the task of green low-carbon transformation and upgrading of Chinese industries remains arduous. In particular, at this stage, all regions should focus on completing the key upgrade of promoting industrial green low-carbon development from end-to-end governance to source transformation and comprehensive structural optimization. The stage of industrial transformation is still faced with problems such as large energy inputs and high emissions, which have exerted great pressure on the regional ecological environment and resources and energy. For example, Zhu et al. (2019) argued that the development trend of advanced and rationalized industry structures is consistent with green economic efficiency, and both have a positive impact on green development efficiency in China. Su and Fan (2022) found that the advancement of the industrial structure has a negative influence on green development with significant effects.

Energy resources are the basis of human economic and social survival and development, and energy, environment and economy are interdependent and mutually constrained. Green economic efficiency is concerned with both quantitative growth and the promotion of quality (Miao et al., 2021; Xia et al., 2021; Adebayo et al., 2023; Kim and Hur, 2023). Scholars typically believe that industrial restructuring is an important reason for the structure of energy use and energy use intensity. Different industries have different degrees of energy dependence, with the secondary industry, especially heavy industry, having the greatest energy demand, and the energy substitutability of high-energy-consumption sectors being extremely low. The substitution of primary energy by secondary energy based on electricity still cannot get rid of the intermediate inputs based on non-renewable energy such as coal. Energy substitution has essentially evolved into the secondary consumption of coal-based primary energy, regional socio-economic development still has the urgent need for emission reduction and kinetic energy conversion. Based on this, in the face of the challenges of energy scarcity, environmental pollution, high energy costs, and the goal of carbon emission reduction, the implementation of the dual-carbon target will become a major strategy for China's transition to a low-carbon economy (Meng et al., 2022; Wang et al., 2023; Yan et al., 2023; Zhang et al., 2023; Zhou et al., 2023). As China is the world's largest energy producer and consumer, energy factors play an important role in influencing green economy efficiency (Hu et al., 2016; Ouyang et al., 2022; Wang, 2023). Lee and Wang (2022) argue that at the provincial level in China, natural resources can positively impact energy sustainability through technological innovation. Ringel et al. (2016) believe that the realization of a green energy economy needs to be based on energy efficiency policies in Germany. Meanwhile, some studies have analyzed the spatially heterogeneous effects of industrial structure distortions on energy intensity, concluding that there is significant regional heterogeneity in industrial structure distortions between eastern, central and western China. It significantly impacts energy intensity and effectively reduces energy use intensity (Shen and Lin, 2021; Xu et al., 2022; Guo et al., 2023). Those studies have shown that industrial transformation has an impact on energy structure and energy efficiency at different scales (Zhang et al., 2020; Lin et al., 2023; Pata et al., 2023; Sun et al., 2023).

Previous studies have analyzed the impact of industrial transformation, energy use, and green economic efficiency from different perspectives. However, there are still some shortcomings. To the best of our knowledge, most of the papers focus on exploring the effect of industrial transformation and energy use on green economic efficiency separately while there is a significant effect of industrial transformation on energy use (Zhou et al., 2013; Wu et al., 2021; Zhu and Lin, 2022), and the path of action between the two has an important impact on the improvement of regional green economic efficiency. There are few studies on the transmission mechanism of industrial transformation on green economic efficiency in the existing results, especially from the mediating role of energy use. Based on this background, it is necessary to further strengthen the influence mechanism of industrial transformation on green economic efficiency from the perspective of energy use as a transmission path. This paper intends to use the SBM-GML model containing non-expected output to measure the green economic efficiency in China and identify the mechanisms and influence paths of industrial structure on regional green economic efficiency based on the analysis of its spatial and temporal change trends, to further enrich the relevant research and provide a reference for promoting regional green development.

In summary, exploring the impact of industrial transformation and energy use on green economic efficiency is crucial to promote regional green, low-carbon transformation, and sustainable development. Thus, the following questions still need to be answered. How does industrial transformation affect green economic efficiency? What are the specific paths of the impact of industrial transformation on green economic efficiency? In addition, what specific impacts have energy use had in this process is also a question of concern. This paper conducts a follow-up analysis based on provinces-level panel data on the industrial transformation and green economic efficiency from 2002 to 2019 in China. We examine the industrial transformation's green effects using a fixed-effects model. This paper further uses a mediating effects model to verify the influence path and regional heterogeneity of energy use. Finally, we proposed countermeasure suggestions for regional green transformation based on industrial policy and energy policy, which can provide policy support for regional sustainable development and high-quality development.

By exploring and addressing the above issues, this paper has the following important marginal contributions. Firstly, this paper focuses on the key role of energy utilization in influencing the efficiency of green economy, and explores the paths and mechanisms through which it works. Secondly, it takes into account the significant differences in economic development, resource endowment and policy planning among the three major regions of East, Central and West China. This paper explores the regional heterogeneity of energy utilization, which can provide a useful complement to the formulation of industrial and energy policies from a regional perspective. Finally, based on practical objectives, we propose policy implications of regional green and low-carbon development, which we hope can provide decision support for the realization of sustainable development goals in different provinces.

The remainder of this paper is organized as follows. Section 2 constructs the theoretical mechanism of the industrial structure affecting green economic efficiency. Section 3 presents the methodology and data sources. Section 4 shows the empirical results. Section 5 provides further analysis, summarizes the research findings and proposes policy implications.

2. Theories analysis and hypotheses

2.1. The direct mechanism of industrial transformation on green economy efficiency

The transformation and upgrading of industrial structure is an important support to promote the efficiency of regional green economy, and its direct impact on green economic efficiency mainly includes two aspects. On the one hand, the effect of advanced industrial structure on green economic efficiency. It promotes the transformation of regional industries to the direction of high value-added, high technology, high intensification and high processing, as well as the transformation of resource-intensive and labor-intensive industries to knowledge-intensive and technology-intensive industries. This process drives technological innovation and optimizes the size and structure of the input-output combination, which increases green economy efficiency (Chung et al., 2022; Herrendorf and Valentinyi, 2022; Song et al., 2022). On the other hand, the effect of industrial structure rationalization on green economy efficiency. The process of industrial structure rationalization is also the process of re-flow and allocation of production factors such as labor, capital, energy and land among industries. The rationalization of the status of industries and the coordination and association between different industries are important manifestations of rationalization (Zhao and Zhang, 2009; Zheng et al., 2022 Chang et al., 2023). According to the theory of the Chenery-Syrquin resource reallocation effect, before the regional economy reaches equilibrium growth, the allocation of production factors between different industries is not the same, making obvious differences in the production efficiency of different industries. The rationalization of industrial structure promotes the gradual transfer of production factors from inefficient industries to high-efficiency industries, and this process will cause changes in regional economic growth, which will further promote green economy efficiency (Mao et al., 2019; Cheng and Li, 2022; Chen D. et al., 2023). Based on this, we propose research hypothesis 1.

Hypothesis 1. (H1). The advanced and rationalized industrial structure has a positive contribution to green economic efficiency.

2.2. The indirect mechanism of industrial transformation on green economy efficiency

Energy utilization optimization can significantly improve the problem of insufficient input or redundant output of green economic efficiency, which is beneficial to the green economic development of the region (Wang et al., 2012; Halder et al., 2015; Fukuyama et al., 2021). Therefore, while the transformation of the industrial structure directly affects regional green economic efficiency, it will also further enhance green economic efficiency by optimizing energy utilization, and the paths mainly include two aspects of energy utilization structure and energy utilization efficiency. Firstly, the advanced and rationalized industrial structure will influence the energy utilization structure through structural and scale effects to promote green economic efficiency. On the one hand, industrial structure transformation can optimize the type and intensity of energy use in different industries. It motivates the gradual reduction of the proportion of resource-intensive industries, labor-intensive industries and other high-energy-consuming industries, and the further increase of the proportion of technology-intensive and knowledge-intensive industries by adjusting the ratio between industries. At the same time, it reduces the use of highly polluting energy sources such as coal and oil, increases the consumption and use of new and green energy sources such as wind, water, tidal and nuclear energy, and contributes existing energy sources to environmental industries to improve the energy use structure (Lin and Tan, 2017; Wu et al., 2019). On the other hand, according to the environmental Kuznets curve, as the level of economic development rises and public demand for a high-quality environment further increases, the increased demand and payments willingness for green products will prompt regional industries to strengthen the use of clean energy and the reduction of pollution emissions (He and Wang, 2012; Bao and Lu, 2022). In summary, hypothesis 2a of the study is proposed.

Hypothesis 2a. (H2a). The advanced and rationalized industrial structure positively influences green economic efficiency by optimizing the energy use structure.

Secondly, the advanced and rationalized industrial structure will affect the efficiency of energy use through technological and spatial effects, which will affect the efficiency improvement of the green economy. On the one hand, the transformation and upgrading of industrial structures are closely linked with better environmental protection technology and high-efficiency technology, which will bring about the progress of production technology and the generation of new technology. The improvement of production technology and the increase of technological content of products can effectively improve production efficiency, enhance the efficiency of energy use, reduce factor inputs and pollution emissions per unit of output, and weaken the negative environmental externalities caused by the production chain (Dong et al., 2020). Meanwhile, the improvement of innovation capacity leads to the development and development of clean and new energy. It raises the efficiency of recycling existing resources and energy and reduces the pollution emission per unit of output. On the other hand, the transformation and upgrading of the industrial structures have spatial and spillover effects. The transformation of industrial structure in the region will bring about the industrial transfer, knowledge spillover and technology spillover, which will influence the energy utilization efficiency of the neighboring regions, and if the neighboring regions obtain faster knowledge innovation and technological progress in the process, this spatial effect will affect the energy efficiency and have a positive impact on the green economic efficiency of the region (Li et al., 2019; Zhou et al., 2019). In summary, hypothesis 2b is proposed.

Hypothesis 2b. **(H2b)**. The advanced and rationalized industrial structure positively contributes to green economic efficiency by enhancing energy use efficiency. The interrelationship between industrial transformation, energy use and green economic efficiency is shown in Fig. 1.

3. Methodology and data

3.1. Measurements of green economy efficiency

Total Factor Productivity (TFP) is a valid measure of economic efficiency. Traditional total factor productivity is used to measure the achievement of efficiency on output increase after all factor inputs such as capital, labor, and land. However, this process does not consider the resource and environmental effects of economic and social development after factor inputs. Therefore, to better measure the efficiency of regional green economic development, we adopt the green total factor productivity (GTFP), which includes non-desired outputs, to represent the real level of regional green development accurately. This paper chose the SBM-Global Malmquist-Luenberger productivity index, which includes non-desired outputs, to measure the green total factor productivity with multiple input indicators and multiple output indicators. The input indicators include capital, energy, and labor, where labor input is represented by the total number of people employed at the end of the year in each province. Energy inputs are expressed using the total energy consumption (converted by the standard coal method). Capital input is represented by the stock of fixed capital. Output indicators are divided into "good" output and "bad" output. The "good" output is the desired output, which is expressed by the regional GDP; the "bad" output is the undesired output, including SO_2 emissions and COD emissions (Table 1). We use MAX-DEA software to measure the GML index which needs to be further processed and calculated to derive the green total factor productivity. Using the 2001 GTFP as the base period and the benchmark value set to 1, the value of green total factor productivity in 2002 is equal to the 2001 productivity multiplied by the GML index in that year. In this way, we can obtain the GTFP of 30 Chinese provinces from 2002 to 2019 by cumulative multiplication year by year.

This paper takes the panel data of 30 provinces (autonomous regions and municipalities directly under the Central Government, excluding Hong Kong, Macao, Taiwan and Tibet) in China from 2002 to 2019 as the sample. The data were mainly obtained from the China Statistical Yearbook, China Environmental Statistical Yearbook, China Energy Statistical Yearbook, as well as the Compilation of Statistics for the Six Decades of New China, the provincial statistical yearbooks and the website of the National Bureau of Statistics. We compiled and calculated the data to form the indicators needed to measure the efficiency of the green economy in each province.

3.2. Mediating effect model

We select a two-way fixed effects panel model to explore the influence mechanism between industrial transformation, energy use and green economic efficiency. First, the baseline regression model is set as follows.

$$\ln GEE_{it} = \alpha_0 + \alpha_1 \ln INS_{it} + \beta X_{it} + \eta_i + \delta_t + \varepsilon_{it} \tag{1}$$

where $\ln GEE_{it}$ is the explained variable, that is, the green economic efficiency of region i in period t; $\ln INS_{it}$ is the core explanatory variable, which is the level of advanced (rationalized) industrial structure in ith region and tth period; X_{it} represents the control variables including technological innovation ($\ln TEC_{it}$), economic development ($\ln ECOit$), openness ($\ln FDI_{it}$), urbanization level ($\ln URB_{it}$), environmental regulation ($\ln ENR_{it}$) and market ($\ln MAR_{it}$). η_i and δ_t represent controlling for individual fixed effects and time fixed effects respectively. ε_{it} is the error term. To test whether energy use is a mediating variable, we chose the step-by-step test method proposed by Baron and Kenny (1986) to analyze the transmission mechanism.

$$\ln EUS_{it} = {\alpha_0}^1 + {\alpha_1}^1 \ln INS_{it} + \beta^1 X_{it} + {\eta_i}^1 + {\delta_t}^1 + {\varepsilon_{it}}^1 \tag{2}$$

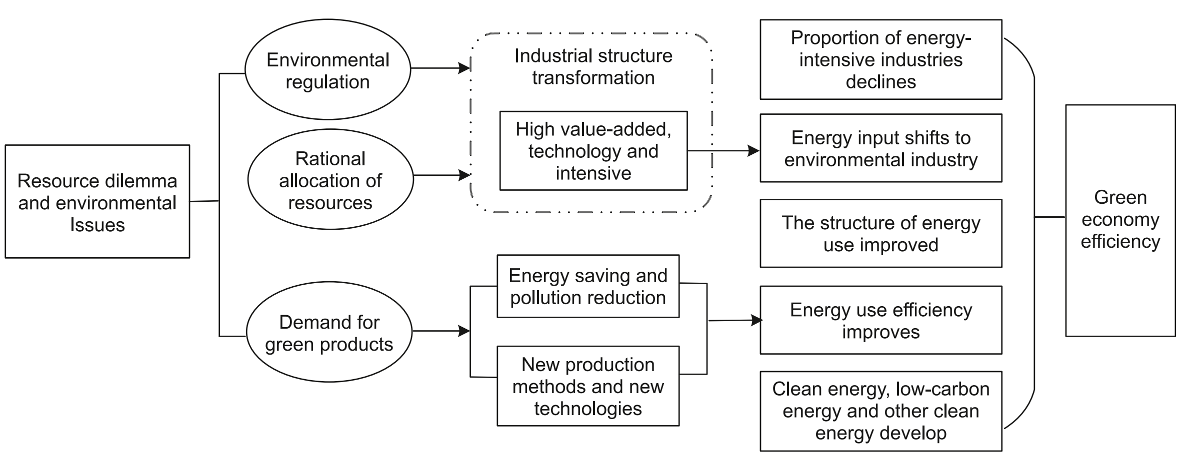

Fig. 1. Influence mechanism between industrial transformation, energy use and green economic efficiency.

Table 1
Input and output indicators and data description of green economic efficiency.

Category	Indicator	Description
Inputs	Capital	Fixed capital stock by region calculated by the perpetual inventory method/billion
	Energy	Total energy consumption by region, converted by the standard coal method/million t
	Labor force	Total employment by region at the end of the year/million people
Expected output	Gross regional product	Total GDP by region/billion RBM
Non-desired outputs	Sulfur dioxide	SO_2 by region emissions per million t
	Chemical oxygen demand	COD emissions by region/million t

$$\ln GEE_{it} = {\alpha_0}^2 + {\alpha_1}^2 \ln INS_{it} + {\alpha_2}^2 \ln EUS_{it} + \beta^2 X_{it} + {\eta_i}^2 + {\delta_t}^2 + {\varepsilon_{it}}^2 \tag{3}$$

$$\ln ENE_{it} = {\alpha_0}^3 + {\alpha_1}^3 \ln INS_{it} + \beta^3 X_{it} + {\eta_i}^3 + {\delta_t}^3 + {\varepsilon_{it}}^3 \tag{4}$$

$$\ln GEE_{it} = {\alpha_0}^4 + {\alpha_1}^4 \ln INS_{it} + {\alpha_2}^4 \ln ENE_{it} + \beta^4 X_{it} + {\eta_i}^4 + {\delta_t}^4 + {\varepsilon_{it}}^4 \tag{5}$$

where Eqs. (1)–(3) constitute the regression process of the mediating effect of energy use structure, while Eqs. (1), (4), and (5) are the models of the mediating effect of energy use efficiency. The stepwise test process for the mediating effect is as follows. The first step is to test the regression coefficient α_1 of Eq. (1). The purpose of this step is to verify the significance of the effect of the core explanatory variables on the explained variables and is a prerequisite for whether to proceed with subsequent tests. The second step examines the regression coefficients ${\alpha_1}^1$ and ${\alpha_2}^2$ of Eqs. (2) and (3) and the coefficients ${\alpha_1}^3$ and ${\alpha_2}^4$ of Eqs. (4) and (5). The purpose of which is to determine whether the mediating effect exists. The third step tests the significance of the coefficients ${\alpha_1}^2$ and ${\alpha_1}^4$ of Eqs. (3) and (5), which are used to determine whether the mediation effect in this process is a fully mediated effect or a partially mediated effect. If the regression coefficient is not significant, it is fully mediated; if it is significant, it indicates that there is also a direct effect in this process, and the partial mediation effect is established. The difference between partial and full mediating effects is that the core explanatory variables of the former can directly influence the explained variables, while this influence process of the latter must rely on the mediating transmission mechanism.

3.3. Variables selection

On the consideration of the availability of data on the indicators of each influencing factor, we established green economic efficiency as the explained variable, selected industrial transformation as the core explanatory variable, energy use as the mediating variable, and also chose control variables such as technological innovation, level of economic development, degree of openness to the outside world, level of urbanization, environmental regulation, and marketization.

Explained variable: green economic efficiency value (*GEE*). Green total factor productivity measured by the SBM-GML index, which includes non-desired outputs, is used as an indicator to characterize regional green economic efficiency.

Core explanatory variables: industrial transformation (*INS*). The factor of industrial transformation is decomposed into two parts: advanced industrial structure (*OIS*) and rationalization (*RIS*), which are calculated according to Eqs. (6) and (7).

$$OIS = \sum_{i=1}^{3} Z_i \times i \tag{6}$$

$$RIS = \sum_{i=1}^{3} \left(\frac{Y_i}{Y}\right) \ln\left(\frac{Y_i}{L_i} \middle/ \frac{Y}{L}\right) \tag{7}$$

where Y_i denotes the output value of industry i, L_i denotes the total number of people employed in industry i, and Z_i is the proportion of the output value of industry i to the total output value of the three industries. According to Eq. (7), when the regional economic development is in equilibrium and the production efficiency among sectors is equalized, there is $RIS = 0$. If the regional industrial structure deviates, the larger the *RIS* value is. At this time, it represents the higher degree of industrial structure deviation, and the unreasonable degree of industrial structure increases accordingly. Therefore, *RIS* is negatively correlated with the degree of rationalization of regional industrial structure, and it will be taken as the inverse in the subsequent regression analysis.

Mediating variables: energy use (*ENS*). Energy use can be decomposed into two aspects: first, energy use structure (*EUS*), which is specifically expressed as the ratio of coal consumption to total energy consumption; second, energy use efficiency (*ENE*), which is expressed as the coal consumption of 10,000 RMB GDP in each region. It is generally assumed that the fewer coal resources consumed in the process of regional economic development, the lower the negative environmental externality will be. Therefore, the two indicators of energy use are taken as the inverse to facilitate the following empirical analysis.

Control variables: Considering that regional green economy efficiency is influenced by various factors such as economic, social, ecological environment, and local policies. In this paper, technological innovation (*TEC*), economic development (*ECO*), openness (*FDI*), urbanization level (*URB*), environmental regulation (*ENR*), and market (*MAR*) are selected as control variables. For technological innovation, the number of regional patents granted is chosen to represent. GDP per capita is used to indicate the level of economic development of each province. The degree of openness to the outside world is represented by regional foreign direct investment, and the level of urbanization is represented by the proportion of the urban population to the total population. Environmental regulation is represented by the proportion of completed investment in industrial pollution control to GDP. The market index is obtained from the China Market Index Database (Beijing National Economic Research Institute, 2022). The descriptive statistics of the variables are shown in Table 2.

To check the smoothness of the panel data time series and avoid pseudo-regression problems during the regression analysis, we used two types of unit root smoothness tests, LLC and IPS. Table 3 shows that all variables passed the LLC and IPS tests, indicating

Table 2
Descriptive statistics of each variable.

Variable	Symbol	Obs	Mean	Std. Dev.	Min	Max
Green economy efficiency	ln*GEE*	540	−0.535	0.372	−1.388	0.762
Advanced industrial structure	ln*OIS*	540	0.831	0.053	0.727	1.030
Rationalization of industrial structure	ln*RIS*	540	1.579	0.736	0.127	4.080
Energy use structure	ln*EUS*	540	0.829	0.442	0.188	3.141
Energy use efficiency	ln*ENE*	540	−0.000	0.841	−2.049	4.109
Technology innovation	ln*TEC*	540	0.757	0.771	0.006	3.534
Economic development	ln*ECO*	540	1.254	0.554	0.243	2.631
Openness to the world	ln*FDI*	540	1.601	1.069	0.056	5.177
Urbanization level	ln*URB*	540	−0.744	0.302	−1.461	−0.109
Environmental regulation	ln*ENR*	540	−2.014	0.756	−5.000	0.144
Market	ln*MAR*	540	1.753	0.321	0.862	2.390

Table 3
Stability test results.

Variable	LLC statistic	P-value	IPS statistics	P-value	Conclusion
ln*GEE*	−2.316	0.010	−7.584	0.000	Stable
ln*OIS*	−2.385	0.008	−2.809	0.002	Stable
ln*RIS*	−4.330	0.000	−1.820	0.034	Stable
ln*EUS*	−22.414	0.000	−3.013	0.001	Stable
ln*ENE*	−4.621	0.000	−2.298	0.010	Stable
ln*TEC*	−3.195	0.000	−2.004	0.022	Stable
ln*ECO*	−5.110	0.000	−1.836	0.033	Stable
ln*FDI*	−2.591	0.004	−1.787	0.036	Stable
ln*URB*	−9.521	0.000	−1.887	0.026	Stable
ln*ENR*	2.475	0.006	−4.133	0.000	Stable
ln*MAR*	−8.487	0.000	−3.922	0.000	Stable

that the panel data test is smooth and ready for the following regression analysis.

4. Empirical analysis

Fig. 2 shows that the trends of green economic efficiency in both full samples and the three regions are roughly U shaped, with different trends in the front and the back part of the research period. The green economic efficiency of the full samples can be approximately divided into two stages with 2016 as the turning point: the first stage is the fluctuating change period (2002–2016). The trend of green economy efficiency shows a state of first decline, then rise, and finally slow decline, with an average annual decline rate of 3.34%. During this period, the development of the country was mainly based on economic growth, but the phenomenon of "GDP-only" emerged in some regions and some fields, overly pursuing the rapid increase of economic aggregates. Although the emphasis was placed on economic development methods and quality, the attention was still insufficient. It has led to the gradual appearance of issues such as tightening of resources, insufficient innovation, and uneven regional development, which has limited the improvement of green economic efficiency; the second stage is the period of rapid rise (2016–2019). Green economic efficiency is raised from 0.665 to 0.823, with an average annual growth rate of 7.90%. Economic development transforms into high-quality development, promotes quality change, efficiency change and power change, accelerates the establishment of an economic system of green, low-carbon and recycling development, and promotes green economic efficiency. The reason for this phenomenon is mainly due to the new development concept of innovation, coordination, green, openness, and sharing, which was put forward in 2015 by the Chinese government. Green development is an important part of it. At the same time, 2016 is also the starting year of the 13th Five-Year Plan for National Economic and Social Development of the People's Republic of China, and the "Accelerating the improvement of the ecological environment" is one of the important chapters. It means that new requirements for promoting the intensive and economical utilization of resources and increasing the comprehensive management of the environment were put forward, which greatly contributes to the level of regional green economic development.

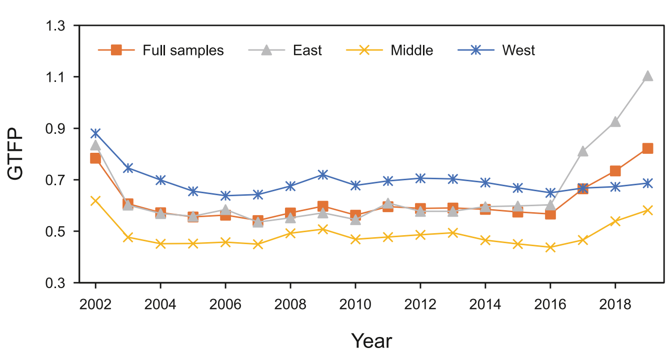

Fig. 2. Regional heterogeneity trend of green economy efficiency.

Provinces have obvious spatial heterogeneity in green economic efficiency due to their different conditions of location, level of economic development, technological innovation, and allocation of production factors. In 2019, 13 provinces such as Tianjin, Shanghai, Jiangsu, Hainan, Chongqing, and Sichuan, were above the national average, concentrated in the eastern and western regions. The high status of Zhejiang Province is particularly prominent, about 3.17 times higher than the national average in that year. The overall spatial pattern of green economic efficiency changes trend is more obvious, and the number of medium and high-efficiency areas dominates. From the perspective of the average annual growth rate of green economic efficiency, 15 provinces such as Beijing, Tianjin, Shanghai, Jiangsu, Zhejiang, and Shandong are positive growth, mainly located in the eastern coastal provinces and the western region; only Henan, Hubei and Hunan in the middle region are positive growth. The negative average annual growth of mid-western provinces such as Shanxi, Inner Mongolia, and Liaoning and the eastern regions of Hebei, Liaoning, Fujian, and Guangxi indicates that the input-output effect of economic development in these regions is lower, and there are problems such as insufficient inputs or redundant outputs. There is a large spatial heterogeneity of green economic efficiency in the three regions compared with the national average, and there are also differences in the average annual growth rate of each province, indicating that China's green economic efficiency has obvious regional distribution characteristics.

We analyzed the impact mechanism of industrial transformation on green economy efficiency by using random effects and fixed effects models and introduced individual fixed effects, time fixed effects, and individual and time double fixed effects in

Table 4
The results of the baseline regression.

Model	Advanced industrial structure		Industrial structure rationalization	
	Without control	With control	Without control	With control
ln*INS*	1.686***	2.301***	0.149***	0.080**
	(5.74)	(5.24)	(6.40)	(2.38)
ln*TEC*		0.231***		0.260***
		(5.81)		(6.45)
ln*ECO*		0.217**		0.324***
		(2.15)		(3.16)
ln*FDI*		−0.132***		−0.163***
		(−4.03)		(-4.89)
ln*URB*		−0.202*		−0.070
		(−1.95)		(−0.69)
ln*ENR*		−0.015		0.009
		(−0.75)		(0.43)
Cons	−1.938***	−2.020***	−0.103	−0.157
	(−7.92)	(−5.07)	(−1.60)	(−0.96)
Province fixed	Yes	Yes	Yes	Yes
Year fixed	Yes	Yes	Yes	Yes
R-squared	0.317	0.378	0.268	0.349
F value	32.95	12.42	9.69	10.98
Hausman	4.12**	14.26**	2.71*	10.20*
Observations	540	540	540	540

Note: $*p < 0.1$, $**p < 0.05$, $***p < 0.01$; t-statistics in parentheses. Same as below.

the fixed effects model (Table 4). The results show that advanced industrial structure has a significant positive impact on green economic efficiency, indicating that every 1% increase in the level of advanced industrial structure will lead to a 2.301% increase in green economic efficiency, controlling for relevant variables. It indicates that the gradual transformation of regional industries from labor-intensive to technology-intensive, knowledge-intensive and capital-intensive industries is beneficial to the improvement of energy efficiency and the decrease of pollution emissions, which further promotes the development of the regional green economy. Columns (3) and (4) show the effect of industrial structure rationalization on green economy efficiency. Without the inclusion of control variables, industrial structure rationalization has a positive contribution to green economic efficiency at 1% significance. After introducing the control variables, industrial structure rationalization is positively correlated with green economic efficiency at 5% significance, and its regression coefficient is 0.080. Every 5% increase in the level of industrial structure rationalization will contribute to a 0.080% increase in green economic efficiency, indicating that industrial structure rationalization can effectively allocate regional energy resources, promote the coordination degree of the ratio of the three industries and the internal division of labor in the industry, and enhance the effectiveness of industrial production.

Among the control variables, technological innovation is significantly and positively correlated with green economic efficiency, indicating that production technology improvement and transformation of innovation results reduce the rate of pollution emission and enhance green total factor productivity. Economic development is positively correlated with green economic efficiency and passes the significance test, showing that an increase in GDP per capita is conducive to an increase in the output of green economic efficiency. Openness has a significant negative correlation with green economic efficiency, which verifies the existence of the pollution havens hypothesis. The pollution havens hypothesis mainly refers to the tendency of enterprises in pollution-intensive industries to establish themselves in countries or regions with relatively low environmental standards. In order to attract more inflows of foreign investments, regions in urgent need of development have introduced a large number of foreign enterprises by relaxing environmental control standards, leading to a continuous acceleration of the exploitation and utilization of local natural resources and the production of more pollution-intensive products (Tummons, 1998; Hamaguchi, 2023; Sánchez-García and Sanz-Lázaro, 2023). Urbanization is not conducive to green economic efficiency, indicating that large population aggregation brings a higher degree of energy consumption and pollution emissions for green development than agglomeration and scale benefits. The effect of environmental regulation on green economic efficiency is negative but not significant.

This paper further uses the intermediary effect test step to carry out the analysis of the transmission mechanism of the industrial structure affecting green economic efficiency. The two-way fixed-effects model is used to explore the mediating effect of energy use structure and energy use efficiency and verify whether energy use acts as a mediating variable in the process of advanced industrial structure influencing green economic efficiency. The specific regression results are shown in Table 5. There is a positive transmission mechanism for both energy utilization structure and efficiency, showing that the advanced industrial structure can significantly improve the energy utilization structure and energy utilization efficiency, which can further promote green economic

Table 5
The results of mediating effect.

Model	ln*GEE*	ln*GEE*	ln*EUS*	ln*ENE*	ln*EUS*	ln*ENE*
ln*OIS*			0.013*	1.828***		
			(1.94)	(2.68)		
ln*RIS*					0.296***	0.575***
					(8.10)	(12.69)
ln*EUS*	0.090**					
	(2.07)					
ln*ENE*		0.009**				
		(3.31)				
Cons	Yes	Yes	Yes	Yes	Yes	Yes
Control	Yes	Yes	Yes	Yes	Yes	Yes
Province fixed	Yes	Yes	Yes	Yes	Yes	Yes
Year fixed	Yes	Yes	Yes	Yes	Yes	Yes
R-squared	0.512	0.518	0.790	0.717	0.531	0.787
F value	21.24	21.81	79.99	54.35	23.18	75.81
Observations	540	540	540	540	540	540

development. On the one hand, there is a significant positive correlation between the improvement and optimization of energy use structure and efficiency and regional green economic development, which can effectively promote green development; on the other hand, in the process of advanced regional industrial structure, energy-intensive industries with heavy pollution and high emissions are gradually reduced and shifted to the direction of industrial development driven by innovation, and the demand for traditional energy sources such as fossil is reduced in this process, and the demand for low-carbon, low-emission and the intensity of the use of low-carbon, low-emission and high-efficiency energy is rising. At the same time, it further contributes positively to the energy input and pollution emission in the process of economic growth, which is conducive to improving the energy use structure. The industrial structure rationalization has a positive contribution to energy use structure and energy use efficiency in the national sample at a 1% confidence level, which is consistent with the results of the benchmark regression. This implies that there is a positive partial mediating effect of industrial structure rationalization.

5. Discussion and conclusions

5.1. Discussion

There are obvious regional differences in natural factor endowments, economic development stages, and industrial structure characteristics among each region in East and Middle-West China. Therefore, we further explored the regional heterogeneity of industrial structure affecting green economic efficiency using a double fixed effects panel regression model. Tables 6 and 7 respectively demonstrate the variability of the mediating effects of energy use in the eastern and middle-western regions of China. Advanced industrial structure has a significant positive effect on the promotion of green economic efficiency in both eastern and middle-western regions. There is regional heterogeneity in the effect of industrial structure rationalization on green economic efficiency, and this result shows a significant positive promotion effect in the eastern region, but a significant negative effect in the middle-western region.

In the heterogeneity test results of the mediating effect, the energy utilization effect is consistent with the national sample in the eastern region. The advanced industrial structure could positively optimize the energy utilization structure and improve the utilization efficiency, while the energy utilization positively promotes green economic efficiency. In the middle-western region, the transmission effect of energy utilization has a significant negative effect; the advanced industrial structure also has a significant negative effect on energy utilization. It may be that the economic foundation of the middle-western region is relatively weaker and the industries are still in the pre-transition stage, which leads to the still higher dependence of regional economic development on traditional energy and high energy consumption industries. At the same time, the technology linkage and balanced development degree between industries vary greatly, which is not conducive to the optimization of energy use structure and the improvement of energy use efficiency, and to a certain extent prevents the development of the green economy.

The effect of industrial structure rationalization on energy utilization structure and energy utilization efficiency in the eastern region is positively promoted at a 1% confidence level, which is consistent with the results of the benchmark regression, indicating that there is a positive partial intermediary effect of industrial structure rationalization in the eastern region. The effect of industrial structure rationalization on energy utilization in the middle-western region is positive at a 1% significance level, and the degree of industrial structure rationalization promotes the optimization of energy utilization structure and efficiency improvement. However, energy use is significantly negatively correlated with green economic efficiency, which is consistent with the results of the baseline regression, that is, there is a negative partial mediating effect of industrial structure rationalization in the middle-western region, indicating that energy use has a hindering effect on the improvement of regional green economic efficiency. At this stage, the economy of the middle-western region is still dominated by secondary industries, especially heavy chemical industries, and the energy consumption structure dominated by coal has not been fundamentally changed. High-energy-input, high-pollution and high-emission industries have affected the development of the green economy. Meanwhile, the industrial transformation has promoted the increase of regional economic scale, which further expands the consumption demand for resources and energy. At this present time, clean and green energy in the middle-western can't totally support the production demand, which leads to large consumption of traditional energy in a short period and hinders the improvement of green economic efficiency. In the future, the middle-western region still needs to adjust the rationalization of regional industries, increase the proportion of low-carbon, clean and efficient energy utilization, improve the efficiency of existing energy utilization, and promote the improvement of green economic efficiency.

Environmental regulation is also a key factor influencing the efficiency of regional green economies. Industrial transformation, energy utilization is an important element of the dual-carbon target concern, and to some extent represents the impact of

Table 6
The results of the mediating effect in eastern region of China.

Model	ln*GEE*	ln*GEE*	ln*EUS*	ln*ENE*	ln*EUS*	ln*ENE*	ln*GEE*	ln*GEE*
ln*OIS*	1.517** (2.11)		5.386*** (4.85)	9.937*** (10.04)				
ln*RIS*		0.217** (4.12)			0.581*** (7.73)	0.534*** (5.64)		
ln*EUS*							0.206*** (3.54)	
ln*ENE*								0.168*** (3.23)
Cons	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Control	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Province fixed	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Year fixed	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
R-squared	0.598	0.617	0.525	0.778	0.635	0.701	0.359	0.351
F value	10.05	10.86	5.06	23.64	11.77	15.86	4.19	4.05
Observations	216	216	216	216	216	216	216	216

Table 7
The results of the mediating effect in the middle-western region of China.

	ln*GEE*	ln*GEE*	ln*EUS*	ln*ENE*	ln*EUS*	ln*ENE*	ln*GEE*	ln*GEE*
ln*OIS*	2.861*** (6.10)		−1.169* (-1.92)	−2.762*** (−5.71)				
ln*RIS*		−0.292*** (−5.74)			0.210*** (5.71)	0.561*** (7.90)		
ln*EUS*							−0.368*** (−4.10)	
ln*ENE*								−0.145*** (−2.92)
Cons	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Control	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Province fixed	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Year fixed	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
R-squared	0.533	0.454	0.4139	0.7522	0.292	0.652	0.4280	0.4100
F value	12.78	9.30	3.38	33.92	5.10	23.14	8.36	7.77
Observations	324	324	324	324	324	324	324	324

environmental policies. Based on this, we next report the results of the impact of industrial structure advancement and rationalization on green economy efficiency under different regulatory intensities. According to the median of environmental regulation intensity, those located before the median are weak environmental regulation, and vice versa, are strong environmental regulation. The results are shown in Table 8. Under stronger environmental regulations, industrial transformation all demonstrated a significant contribution to the efficiency of the green economy. Energy utilization efficiency also showed a significant positive effect. However, under weaker environmental regulations, industrial transformation fails to influence green economic efficiency. Energy use has a significant promotional effect, probably due to the fact that environmental policies in this phase did not impose strong restrictions on energy use and the regional economy developed more rapidly.

This paper quantitatively examines the impact of industrial transformation on the efficiency of the green economy and focuses on the key role of energy utilization, but there are some improvements that can be made. On the one hand, carbon neutrality has become a hot topic in the world. The realization of the dual carbon goal involves one or more areas such as industry, energy, buildings, transportation, agriculture, and carbon sinks. This paper has only focused on two areas, industry and energy. In the future, further in-depth studies on other fields are still needed, given the conditions of technical feasibility and data availability. On the other hand, this paper focuses on industrial transformation and energy utilization at the provincial scale, and there is a need to carry out green and low-carbon transformation in different industries based on industry heterogeneity, which provides space for subsequent research.

5.2. Conclusions and policy recommendations

This paper measures the provincial green economic efficiency and its trend using the SBM-GML model with non-expected output and examines the mediating effect of energy use and its regional heterogeneity using a two-way fixed panel effects model. The conclusions can be summarized as follows.

Firstly, the green economic efficiency of the full samples and the three regions of east, west and middle shows a general U shape trend. The average annual growth rate of GEE of the full sample increased from −3.34% to 7.90%, and the green economic efficiency of the eastern region was 1.34 times higher than the national average in 2019; green economic efficiency has obvious regional distribution characteristics in space, showing the trend of “eastern region > western region > middle region”. The number of regions in the middle and high efficiency dominates.

Secondly, the advanced and rationalized industrial structure has a significant positive impact on green economic efficiency. The improvement and optimization of energy utilization structure and energy utilization efficiency are positively related to green economic efficiency. The advanced and rationalized industrial structure can positively promote energy use, indicating that both energy

Table 8
The results of the different regulatory intensities.

Model	ln*GEE*	ln*GEE*	ln*GEE*	ln*GEE*	ln*GEE*	ln*GEE*	ln*GEE*	ln*GEE*
	Weak environmental regulation				Strong environmental regulation			
ln*OIS*	0.318 (0.33)				1.059* (1.65)			
ln*RIS*		0.019 (0.46)				0.007* (1.89)		
ln*EUS*			0.015* (1.94)				0.017 (1.19)	
ln*ENE*				0.007** (2.28)				0.105*** (3.10)
Cons	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Control	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Province fixed	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Year fixed	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
R-squared	0.474	0.474	0.483	0.486	0.613	0.605	0.613	0.627
F value	8.58	8.59	8.89	9.00	17.48	17.84	16.58	15.90
Observations	270	270	270	270	270	270	270	270

use structure and energy use efficiency have positive partial mediating effects in the process of an advanced and rationalized industrial structure affecting green economic efficiency.

Finally, from the regional heterogeneity test, the impact effect of advanced industrial structure and rationalization in the eastern region is consistent with the full sample. It has a positive effect on green economic efficiency, and its influence path is also a positive partially mediated effect; however, this path is different from the test results in the middle and western regions, and energy utilization has a negative effect on green economic efficiency enhancement. The advanced industrial structure is significantly negatively related to energy utilization and has a significant positive effect on green economic efficiency, while rationalization of industrial structure has a significant negative effect on energy utilization and a negative relationship with green economic efficiency, which is a negative partial intermediary effect.

The following policy recommendations are based on the above conclusions:

Firstly, energy utilization technology research and development and application should be vigorously developed, and green energy should be promoted as a substitute for non-renewable energy. Strongly develop green energy industries such as hydropower, wind power, solar power, nuclear power, accelerate the research and development of green energy production technology, accelerate the construction of a modern energy system that is clean, low-carbon, safe and efficient, and promote the "dual-control" of energy consumption to the "dual-control" of the total amount and intensity of carbon emissions.

Secondly, strongly promote the transformation and upgrading of energy-intensive industries in the middle and western regions, and break the "resource curse". The mid-western region is limited by factors such as resource development, infrastructure construction and population, and its economic development is backward compared with that of the eastern region. On this basis, the mid-western and western regions should break down the obstacles and barriers to the interregional flow of factors, promote the green and low-carbon transformation of the region's industrial and energy structures and accelerate the cultivation of emerging industries such as new-energy automobiles, intelligent manufacturing and biomedicine, through the introduction of the advanced technologies and management experience of the eastern region and the attraction of high-level talent inflows.

Thirdly, strengthening national and local policy support regarding funding, talent, technology and safeguard mechanisms. On the basis of comprehensive consideration of factors such as economic growth, industrial structure adjustment, energy structure optimization, and synergistic control of air pollutant emissions in each region, establish a guarantee mechanism for cross-regional exchanges and cooperation, and improve infrastructure and intermediary circulation. Strengthen control of energy consumption, realize low-carbon technological innovation, and enhance the effectiveness of carbon emission reduction and promote the regional green economy efficiency.

CRediT authorship contribution statement

Jin-Xing Jiang: Writing – original draft, Data curation. **Jing-Jing Wang:** Writing – review & editing, Software, Methodology. **Yu Cheng:** Writing – review & editing, Project administration, Funding acquisition.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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