Research on the mechanism of Energy use efficiency on New quality productive forces based on the perspective of R&D intensity

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Abstract. In the context of the profound transformation of the global energy landscape and the iterative enhancement of productivity, the effective improve of New quality productivity, the propulsion of the economy towards high-quality development, and the navigation of the "growth impediment" have emerged as pivotal concerns for diverse societal segments worldwide. Given the heterogeneity in the developmental stage of new productivity across regions, this paper utilises panel data from 31 provinces in China from 2010 to 2022, and categorises the developmental level of new productivity into three tiers: high, medium and low. The findings indicate that, firstly, energy use efficiency has the capacity to stimulate the advancement of new quality productivity. Secondly, the promotion effect of energy efficiency on New quality productive forces is more significant in regions with medium and high New quality productive forces development levels. Thirdly, it is demonstrated that Energy use efficiency can contribute to the improvement of New quality productivity by improving the development of R&D intensity. The paper puts forward policy recommendations from three perspectives: policy support and guidance, technological innovation and promotion, and industrial restructuring and upgrading.

Keywords: Energy use efficiency, New quality productive forces, R&D intensity, Mediating effect.

1. Introduction

In the era of profound changes in the global economic and scientific and technological landscape, Energy use efficiency and New quality productive forces have become the core elements to promote social progress and realize sustainable development, and the research on the correlation between the two is of far-reaching significance.

New quality productive forces as advanced productive forces to adapt to the development needs of the new era, emphasizing the quality and efficiency of development. The New quality productive forces take the basic connotation of laborers, labor materials, labor objects and their optimized combination, and emerge from revolutionary technological breakthrough, innovative allocation of production factors, and deep transformation and upgrading of industries. Numerous scholars have studied the New quality productive forces, New quality productive forces represents the new direction of productivity development, which can break the limitations of the traditional production model and reshape the industrial value chain [1], Emphasized that the New quality productive forces at the industrial level manifests itself in the rise of emerging industries and the high-end conversion of traditional industries, which is of great significance to the optimization of economic structure [2]. The study shows that the New quality productive forces prompts the traditional industries to accelerate the conversion to digitalization and greening, and shapes a new engine to promote the continuous, stable and healthy development of China's economy [3]. Improve the institutional mechanism for developing new productivity in accordance with local conditions, and to improve the agglomeration of all kinds of advanced elements of production into new productivity, which will sensibly increase total element productivity [4]. However, most of the current research on New quality productive forces focuses on the meaning, characteristics and single driving factors, and there is less discussion on its relationship with Energy use efficiency.

Energy use efficiency is also of great concern. As the power source of economic operation and a basic factor of production, it is crucial to promote Energy use efficiency. With the promotion of the "dual-carbon" goal and the aggravation of energy and resource constraints, improving Energy use efficiency has evolved into an inevitable choice for China to complete green economic transformation and sustainable development. Previous studies on Energy use efficiency have focused on its impact on economic growth and environmental quality. Improved Energy use efficiency can reduce production costs and raise the green competitiveness, which in turn promotes economic growth [5]; Through empirical analyses that efficient energy use reduces pollutant emissions, improves the environment, and creates excellent conditions for the sustainable development of the economy [6]. Study using an econometric model, and the results showed that improving the quality of industrial restructuring has a significant promotional effect and spatial spillover effect on Energy use efficiency, while expanding the magnitude of industrial restructuring has an obvious blocking effect on Energy use efficiency [7]. Energy conservation and improve Energy use efficiency is of great significance to promote high-quality development, not only to enhance the quality and efficiency of economic development, is an important guarantee to maintain the security of development, and it is the rightful meaning to enhance the well-being of people's livelihood [8]. However, there is a relative lack of research that closely links Energy use efficiency with New quality productive forces and explores its impact on New quality productive forces.

To summarize, it is urgent and important to study in depth the mechanism of the influence of Energy use efficiency on New quality productive forces. Therefore, this paper intends to use quantitative research methods to empirically test the effect of Energy use efficiency on New quality productive forces and the mediating effect of R&D intensity between the two. The influence of Energy use efficiency on New quality productive forces is empirically examined by constructing a two-way fixed effects model. This paper makes the following contributions: first, it empirically tests that Energy use efficiency has a positive impact on New quality productive forces. Second, there are significant differences in the effect of Energy use efficiency and energy consumption scale on the improvement of New quality productive forces at different stages of New quality productive forces, with the low stage being insignificant and the middle and high stages being significantly positively correlated. Third, R&D intensity is quantified to analyze its mediating effect in the path of Energy use efficiency affecting New quality productive forces. Through this multifaceted discussion, we provide countermeasure suggestions for promoting Energy use efficiency to develop New quality productive forces.

2. Study hypotheses and the experimental design

2.1. Study hypotheses

2.1.1 Theoretical analysis of Energy use efficiency and New quality productive forces

Starting from the basic logic of production theory, Energy as a key component of production factors, has multiple positive effects from the improvement of its utilization efficiency. An increase in Energy use efficiency means that energy consumption can be reduced while output remains constant [9]. Zhang Sichin ; Improving Energy use efficiency not only reduces the production cost and enhances their strength in the market, but also releases more resources for optimization and innovation in other production processes [10]. From the macroeconomic level, when the Energy use efficiency of many enterprises is generally improved, the productivity and innovation capacity of the whole industry and even the national economy will be enhanced, which in turn will improve the overall growth of New quality productive forces. Therefore, based on the above analysis at the theoretical and practical levels, we propose the hypothesis H1, which expects that Energy use efficiency can have a influence positive impact on the New quality productive forces.

H1: Energy use efficiency can have a direct positive impact on New quality productive forces.

At the low development stage of New quality productive forces, the level of technology is backward, with the crude production mode dominating. At this time, the ability of technology to transform energy is limited, and even if the Energy use efficiency is improved to a certain extent, the overall inefficiency of the production system makes it difficult to have a significant effect on the enhancement of New quality productive forces.

However, when the growth of New quality productive forces enters the middle and high stages, the proportion of high-end manufacturing and strategic emerging industries increases, and the ability for technological innovation also improves significantly.Based on the above points, we put forward the hypothesis H2, that in different stages of New quality productive forces, the effect of Energy use efficiency and energy consumption scale on the improvement of New quality productive forces has a significant difference, the low stage is not significant, and the middle and high stages are significantly positively correlated.

H2: There is a obvious difference in the influence of Energy use efficiency and the scale of energy consumption on the improvement of New quality productive forces at different stages of New quality productive forces, which is not significant at the low stage and is significantly positively correlated at the middle and high stages.

The New quality productive forces takes science and technology innovation as thecore driving force, emphasizing technological progress and innovation to improve production efficiency, product quality and economic benefits in all aspects. High-intensity R&D investment can often give rise to a series of positive results such as technological breakthroughs, process improvement and product innovation, but also through the knowledge spillover effect and the synergistic development of the industrial chain [11].

To summarize, the advance of Energy use efficiency can increase R&D investment, and then enhance the intensity of R&D, and the enhancement of R&D intensity will further promote the growth of New quality productive forces, the intensity of R&D is the key intermediary link in the influence of Energy use efficiency on New quality productive forces. Based on the above research, we put forward hypothesis 3, further study the connection and mechanism between the three.

H3: R&D intensity plays a mediating role in the progress of Energy use efficiency and the development of New quality productive forces.

2.2. Experimental design

2.2.1 Selection of variables

Explained variable: New quality productive forces (NQP). New quality productive forces is high-quality productivity achieved through technological creation, resource allocation optimization and industrial structure upgrading. Adopts the New quality productive forces indicator system constructed as a proxy variable. This indicator system integrates multiple dimensions such as technological innovation, resource allocation efficiency, and industrial structure upgrading, which can comprehensively reflect the connotation of New quality productive forces [12].

Core explanatory variables: Energy use efficiency (EE). Chooses total factor Energy use efficiency as the explanatory variable. The Super-SBM model, which includes non-desired outputs, is mainly used to measure total element Energy use efficiency, with labor force, capital stock, and energy as input factors, the GDP of each province as desired outputs, and the wastewater emission, sulfur dioxide emission, and soot emission as non-desired outputs [13].

Mediating variable: R&D intensity (RDI). R&D intensity has a direct influence on the capacity for technological innovation, which in turn affects Energy use efficiency and New quality productive forces. A high R&D intensity usually means that more resources are devoted to technological R&D, which in turn drives technological progress and Energy use efficiency. This paper quantifies R&D intensity by measuring the share of science and technology expenditure in GDP.

Control variables. In order to avoid other factors that may affect the New quality productive forces, the Industrial structure upgrading index (ISU), Openness Level to the Outside World (OPL), and The degree of government intervention (GI) are also controlled. Structure upgrading index (ISU)

[14]. Specifically, the entropy weight method is used to assign different weights to the rationalization of structure and the advanced industrial structure, and then a comprehensive index of industrial structure upgrading is calculated comprehensively [15]. Among them, industrial structure sophistication is measured by the ratio of the output value of tertiary industry to that of secondary industry, which can more accurately show the overall direction of structure change; industrial structure rationalization is measured by the improved Thiel index, which evaluates the degree of synergy between industries as well as the effectiveness of factor inputs in industries. Variable definitions and calculation methods are summarized in Table 1.

Table. 1. Summary of variable definitions and calculation methods

Variable name	Abbreviation of letters	Calculation method	Unit (of measure)
New quality productive forces	NQP	Based on the index system constructed by Ren Yuxin, Wu Yan, and Wu Zhe (2024), synthesizing the dimensions of technological innovation, resource allocation efficiency, and industrial structure upgrading	Composite index (e. g. Dow Jones or Nikkei index)
Energy use efficiency	EE	Total factor Energy use efficiency was measured using the Super-SBM model including non-desired outputs, with input factors being labor, capital stock, and total energy consumption, desired outputs being GDP, and non-desired outputs being wastewater, sulfur dioxide, and soot emissions	Efficiency value (unitless)
R&D intensity	RDI	Science and technology expenditure as a share of GDP	Percentage (%)
Industrial structure upgrading index	ISU	Indicators of rationalization (improvement of the Thiel index) and sophistication (tertiary/secondary output ratio) of the integrated structure based on the entropy weight method	Composite index (e. g. Dow Jones or Nikkei index)
Openness level to the outside world	OPL	Each region measures its level of openness to the outside world according to the proportion of total imports and exports of the location of the business unit to GDP, and the amount of investment is converted into ten thousand yuan based on the exchange rate of the current year.	Percentage (%)
Level of government intervention	GI	Measuring Government Intervention Using Fiscal Revenues as a Share of GDP by Region	Percentage (%)

2.2.2 Model building

On the one hand, explore the impact of EE on the NQP, a benchmark regression model is constructed as follows: benchmark regression with two-way fixed effects:

$$NQP_{it} = \beta_0 + \beta_1 * EE_{it} + \mu_i + \lambda_t + \varepsilon_{it} \tag{1}$$

Two-way fixed effects and baseline regression with control variables:

$$NQP_{it} = \beta_0 + \beta_1 * EE_{it} + \beta_2 * ISU_{it} + \beta_3 * OPL_{it} + \beta_4 * GI_{it} + \mu_i + \lambda_t + \varepsilon_{it} \quad (2)$$

Where i and t represent provinces, cities, autonomous regions and time respectively; NQP_{it} is the NQP of the i region at time t (the explanatory variable); EE_{it} is the energy efficiency of region i at time t (core explanatory variable); ISU_{it} , OPL_{it} , and GI_{it} are the index of structure upgrading, the level of opening to the outside world and the degree of government intervention, respectively, μ_i stands for area fixed effects, λ_t stands for time fixed effects, ε_{it} is the random interference term. β_0 is the representative intercept term and β_1 , β_2 and β_3 the estimated coefficients.

On the other hand, investigate the mechanism of NQP on energy efficiency, the mediating effect model is constructed on the basis of equation (1) as follows:

$$RD_{it} = \alpha_0 + \alpha_1 * EE_{it} + \alpha_2 * ISU_{it} + \alpha_3 * OPL_{it} + \alpha_4 * GI_{it} + \mu_i + \lambda_t + e_t \quad (3)$$

$$NQP_{it} = \theta_0 + \theta_1 * EE_{it} + \theta_2 RD_{it} + \theta_3 * ISU_{it} + \theta_4 * OPL_{it} + \theta_5 * GI_{it} + \mu_i + \lambda_t + \mu_{it} \quad (4)$$

where RD_{it} represents the mediating variable, i. e. , R&D intensity; where both α_1 and θ_2 are significant, if θ_1 is not obvious, it indicates a fully mediated effect; If θ_1 is obvious and $\theta_1 < \beta_1$, existence of a partial effects model, i. e. , energy efficiency is able to influence the development of NQP by affecting the mediating variable.

3. Empirical analysis

3.1. Data sources and pre-processing

The sample of this paper is the panel data of 31 provinces, municipalities and autonomous regions from 2010 to 2022, and the original data are from China Urban Statistical Yearbook, China Energy Statistical Yearbook, China Industrial Statistical Yearbook, and statistical yearbooks of provinces and municipalities, and the missing values are filled in by linear interpolation method. The descriptive statistics of the distributional characteristics of the variables are shown in Table 2.

Table. 2. Descriptive statistics of variables

Variant	Number of observations	Average value	Standard deviation	Minimum value	Upper quartile	Maximum values
EE	390	0.7685	0.1982	0.0000	0.8208	1.0000
ISU	390	2.3751	0.1308	2.1265	2.3632	2.8359
OPL	390	0.2765	0.2906	0.0076	0.1462	1.4638
GI	390	0.2571	0.1113	0.1050	0.2304	0.7583
RDI	390	0.0215	0.0151	0.0039	0.0143	0.0676
NQP	390	0.2856	0.1311	0.1000	0.2545	0.7473

3.2. Regression results and correlation test

3.2.1 Analysis of baseline regression results

The two-way fixed-effects model effectively solves problems such as omitted variables by controlling individual and time fixed effects in researching the influence of EE on NQP, and provides a reliable method for studying the relationship between the two. Meanwhile, in the study of the relationship between EE and NQP, adding control variables is to more accurately reveal the intrinsic connection between the two, avoid estimation bias, and enhance the conclusions of the study reliability and validity of the research conclusions.

Controlling for individual fixed effects and time fixed effects, tested for stability of the coefficient of influence of EE by means of a baseline regression model with two-way fixed effects in Table 3. It shows that EE can strengthen the NQP, and hypothesis H1 is validated.

Table. 3. Benchmark regression results for two-way fixed effects

	(1)	(2)
EE	0.1201*** (4.56)	0.1755*** (4.56)
Control Variable	NO	YES
year	YES	YES
id	YES	YES
n	390	390
R2	0.3734	0.4106
F (P)	15.91***	14.98***

Note: ***, ** and * indicate that the coefficients are significant at the 1%, 5% and 10% levels,respectively. Standard errors are in parentheses, the following table is the same.

3.2.2 Robustness tests

Robustness Tests. This research adopts three robustness tests to prove the reliability of the impact of EE on NQP. First, the inclusion of the first-order lag term of the NQP in the robustness test can effectively control the dynamic change characteristics of the NQP itself and the impact of the previous state on the current period, avoiding the estimation bias due to the omission of such a dynamic effect, so as to make the estimation of the influence of the EE on the NQP more accurate. Secondly, the test using the NQP data of odd-even years can examine whether the model results are stable from the perspective of different sample distributions in the time dimension. The test results of both methods show that EE has a obvious impact on the improvement of NQP, which verifies the robustness and reliability of the model in Table 1.

Table. 4. Robustness test

	(1) Add lags	(2) even year	(3) odd-numbered year
EE	0.1272 *** (3.62)	0.0854 *** (2.33)	0.1967 *** (5.74)
Control Variable	YES	YES	YES
year	YES	YES	YES
id	YES	YES	YES
n	390	210	180
R2	0.4238	0.4395	0.2896
F (P)	15.44***	13.33***	6.39***

3.2.3 Endogeneity test

In the study of this paper, there may be a bidirectional causality between EE and NQP, which leads to the endogeneity problem. In addition, omitted variables (e. g., technological innovation, policy environment, etc.) may also cause the core explanatory variables to be correlated with the error term, further exacerbating the endogeneity problem. This paper adopts the instrumental variable (IV) way to mitigate the endogeneity problem, and two instrumental variables are selected for testing respectively.

First instrumental variable: EE with a one-period lag. There is inertia in the economic system and EE may be autocorrelated in the time series. Incorporating a first-order lag term can control the potential impact of EE in the previous period on NQP in the current period, avoid endogeneity bias caused by omitting important variables, and then accurately identify the causal relationship between the two,results are shown in Table 5 (1).

Second instrumental variable: coefficient of variation of EE.In Table 5(2), the regression results of the instrumental variables approach indicate that the positive effect of EE on NQP is robust and the endogeneity problem is effectively controlled. Through the instrumental variables approach, this paper effectively controls the possible endogeneity problem between EE and NQP. The empirical results show that the beneficial effect of EE on NQP is robust and the research findings are highly reliable.

Table. 5. Endogeneity test

	(1)	(2)
EE	0. 2745 *** (4. 11)	0. 1198*** (4. 13)
IV	0. 3721 *** (9. 95)	10. 5262 *** (28. 15)
Control Variable	YES	YES
year	YES	YES
id	YES	YES
n	390	390

3.2.4 Heterogeneity analysis

In this paper, the NQP of provinces, municipalities and autonomous regions in China is categorized into three levels through cluster analysis: medium level, high level and low level. It is found that there are obvious differences in the role of EE in different stages of NQP. At the low level of NQP stage, the effect of EE on productivity is insignificant, as shown in Table 6(3), while at the medium and high level of NQP stages, the effect of EE is significantly positive, as shown in Table 6(1) and Table 6(2). This heterogeneity may stem from the following aspects: first, high-level NQP regions usually have stronger technological absorption and innovation capabilities and are able to translate EE gains into productivity growth more effectively. Low-level regions, on the other hand, have energy efficiency difficulty in fully utilizing the potential gains from EE improvements due to their weak technological base.

Second, high-level NQP regions tend to be dominated by high-technology industries or services, which are more sensitive to EE and where EE improvements can significantly reduce production costs and increase output. Low-level regions, on the other hand, may still be dominated by traditional industries or resource-intensive industries, and EE improvements will have a limited impact on productivity.

Table. 6. Heterogeneity analysis

	(1) Medium level	(2) High level	(3) Low level
EE	0.0677 *** (1.96)	0.2969 *** (4.87)	0.0641 (1.62)
Control Variable	YES	YES	YES
year	YES	YES	YES
id	YES	YES	YES
n	390	390	390
R2	0.3734	0.4106	0.2185
F (P)	17.22***	14.98***	2.87

3.2.5 Mechanism test - mediation effect test

The regression results of EE (EE) on R&D intensity (RDI) show that EE has a significant beneficial promotion effect on R&D intensity, as shown in Table 7 (1). It means that the advance of

EE will drive more resources into R&D activities, increase R&D intensity, provide strong support for R&D intensity, and then affect the development of NQP.

Table. 7. Analysis of intermediation effects (summary)

	(1)	(2)
EE	0.2968*** (6.02)	0.0897*** (3.36)
RDI		0.0939*** (3.38)
Control Variable	YES	YES
year	YES	YES
id	YES	YES
n	390	390

When both EE and RDI are included in the model, the effect of RDI on NQP is significant, and the influence of EE on NQP is still significant, as shown in Table 7(2), but with the coefficients decreasing compared to Table 7(1), this suggests that R&D intensity plays a partial mediating role in the process of energy efficiency affecting NQP.

Using Sobel-Goodman mediation effect analysis, RDI is used as a mediating variable to explore the mechanism study of the impact of EE on NQP, and the results of the research are shown in Table 8. further highlighting the important mediating role of R&D intensity in the relationship between EE and NQP.

Table. 8. Results of the research of intermediary effects

	Coef	Std Err	Z	P>|Z|
First-stage	0.2968	0.0493	6.0228	1.7e-09
Two-stage	0.0939	0.0278	3.3759	0.0007
Indirect effect	0.0279	0.0095	2.9448	0.0032
Direct effect	0.0897	0.0267	3.3556	0.0008
Total effect	0.1176	0.0258	4.5560	5.2e-06

4. Conclusions

This paper finds that, first, EE has a significant positive impact on NQP. The improvement of EE directly promotes the development of NQP. Second, there is significant regional heterogeneity in the promotion of EE. In regions with low levels of NQP, the marginal effect of EE improvement is low, and it is difficult to significantly promote productivity upgrading; whereas in regions with medium and high levels of development, EE improvement to be embedded into the production system more efficiently, the The advance of NQP is significantly accelerated. Third, R&D intensity plays a significant mediating effect between EE and NQP. In summary, this research puts forward the following countermeasure suggestions:

(1) The formulation of EE-related policies. The Government should develop policies to encourage the efficient use of energy. Tax incentives should be given to enterprises adopting advanced energy-saving technology and equipment, carrying out energy management system construction; subsidies should be given to enterprises and consumers implementing energy-saving projects and promoting the use of energy-saving products.

(2) we should increase investment in research, popularize the application of energy technologies. The government should increase support in energy technology, incorporate it into national planning, fitting on direction and goals of R&D, increase financial allocations, set up special funds, encourage to invest in R&D. Enterprises as the main body of R & D, the establishment of long-term investment

mechanism, training and introduction of talent, around the market demand to overcome key technical challenges.

(3) Differentiated regional policies should be implemented to narrow the gap in the development of NQP and achieve coordinated regional economic development. In regions with low levels of New quality productive forces, focus on strengthening technological infrastructure and structure optimization, increasing investment in infrastructure construction; In regions with medium and high levels of development, further promote industrial upgrading and high-end transformation.Also, it will drive the common progress of other surrounding areas, play a supportive role, help low-level areas in the surrounding areas improve their own strength, and promote the overall high-quality development of the economy.

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