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Research on the Impact of Green Patenting Activities on Urban Energy Efficiency

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Abstract

Under the dual constraints of the "dual carbon" goals and energy security, local governments have taken the improvement of urban energy efficiency as an important tool to promote China's green and low-carbon transition. This paper uses 270 prefecture-level and above cities in China from 2014 to 2023 as the research sample. It constructs a comprehensive index of urban energy efficiency, and mainly examines the actual impact of green patenting activities on urban energy efficiency. It also further tests the mediating role of energy conservation and environmental protection expenditure between the two. The results show that green patenting activities can significantly improve urban energy efficiency. Energy conservation and environmental protection expenditure plays a partial mediating role in this relationship. These effects are more evident in cities located in eastern China and on the southeast side of the Hu Huanyong Line. Based on these findings, this paper argues that green patenting activities can serve as an important endogenous force for improving urban energy efficiency. Fiscal expenditure can also act as a key policy lever. It can help transform different types of innovation outcomes into actual energy-saving performance. These empirical findings provide useful references for local governments to improve innovation incentives and allocate green fiscal resources more effectively.

Keywords

Green patenting activities; energy conservation and environmental protection expenditure; urban energy efficiency

1. Introduction

Energy efficiency affects not only the efficiency of resource allocation, but also the actual performance of urban green transition. With the continuous advancement of the dual carbon goals, Chinese cities have become key spatial units of energy consumption, industrial agglomeration, and technological innovation. How to reduce energy use per unit of output through technological progress has long been a common concern for both scholars and policymakers. Compared with the traditional path that mainly relies on factor inputs and administrative reduction measures,

green patenting activities place more emphasis on technological substitution, process improvement, and cleaner production. These channels can improve long-term efficiency, and therefore have stronger sustainability and endogeneity.

Existing studies have discussed the environmental performance of technological innovation from different perspectives, such as urban green development, eco-efficiency, carbon emission efficiency, and energy efficiency. At the same time, fiscal expenditure, especially energy conservation and environmental protection expenditure, is considered to reduce the costs of green technology R&D and diffusion through subsidies, public infrastructure construction, and policy guidance. In this way, it can further improve the efficiency of green transition. However, two gaps remain in the existing literature. First, many studies directly examine the relationship between technological innovation and green development, or between technological innovation and carbon efficiency. Direct evidence on the relationship between green patenting activities and urban energy efficiency at the prefecture-level city scale is still relatively limited. Second, it remains unclear whether fiscal expenditure improves energy efficiency directly, or whether it works indirectly by promoting the transformation of green innovation outcomes. More empirical evidence is still needed.

Based on this, this paper takes 270 prefecture-level and above cities in China from 2014 to 2023 as the research sample. It uses a two-way fixed effects model to examine the impact of green patenting activities on urban energy efficiency. It further tests the mediating effect of energy conservation and environmental protection expenditure, as well as regional heterogeneity. Compared with the previous version, this paper highlights the main line of green patenting activities, fiscal expenditure, and urban energy efficiency in its structure. It also reduces repetitive policy descriptions and general background discussion. As a result, the argument becomes more compact and coherent.

2. Literature Review and Research Hypotheses

2.1. Green Patenting Activities and Urban Energy Efficiency

Existing studies at home and abroad have reached a relatively consistent conclusion on whether technological innovation can improve urban green performance. Porter and van der Linde (1995) argue that moderate environmental constraints can induce firms to carry out technological innovation, and may generate innovation compensation in the long run. Jaffe, Newell and Stavins (2005) further point out that environmental policy and technology policy often need to work together, so as to correct both environmental externalities and innovation externalities. From the perspective of energy technology, Popp (2002) uses patent data and finds that changes in energy prices can induce firms to develop energy-saving technologies. Berrone et al. (2013) also show that firms' green invention activities can be significantly promoted under institutional pressure.

In the Chinese context, related studies have examined this issue from the perspectives of urban green development, eco-efficiency, and energy efficiency. Zhang et al. (2018) use a spatial econometric analysis of 105 cities and find that technological innovation can significantly promote urban green development, with clear spatial spillover effects. Wang and Wang (2020), based on a dynamic panel of 284 cities, also show that technological innovation has a robust positive effect on energy efficiency. Du, Cheng and Yao (2021) focus on the relationship between environmental regulation and urban transition. They find that environmental regulation can promote urban green transition through green technological innovation and industrial structure upgrading, but this effect differs across stages of economic development. Shang et al. (2022) further point out that the spillover effect of green technological innovation can promote the convergence of urban eco-efficiency. This suggests that green innovation has not only local effects, but also cross-regional diffusion effects. Fang et al. (2022), using a sample from the Yangtze River Economic Belt, also find that green innovation can significantly improve urban carbon emission efficiency, and that this effect shows regional heterogeneity.

2.2. Fiscal Expenditure, Green Innovation, and Energy Efficiency

Fiscal expenditure is an important policy tool in the process of promoting green transition. Lin and Zhu (2019) find that the structure of fiscal expenditure has a significant impact on green economic growth performance. This finding shows that government expenditure is not simply a cost of public spending. It can also promote green development by improving resource allocation and public service provision. Wei et al. (2023), based on an empirical analysis of Chinese cities, also find that fiscal expenditure can significantly promote green technological innovation. However, the extent of this effect is constrained by the city's stage of development and the structure of fiscal expenditure. Fang et al. (2024) use a sample of 254 cities and reach a similar conclusion. They find that green fiscal expenditure can significantly improve green total factor energy efficiency, and that this policy effect can be further strengthened through channels such as industrial upgrading and the digital economy. These studies show that energy conservation and environmental protection expenditure can not only directly improve energy infrastructure and environmental governance, but also indirectly enhance overall energy efficiency by supporting the application and transformation of green innovation outcomes.

However, existing studies focus more on the one-way relationship between fiscal expenditure and green innovation, or between fiscal expenditure and green total factor energy efficiency. There is still a lack of direct city-level evidence on whether energy conservation and environmental protection expenditure plays a mediating role in the impact of green patenting activities on urban energy efficiency. Based on this, this paper incorporates fiscal expenditure into the same analytical framework to identify its bridging effect.

2.3. Literature Review and Research Hypotheses

Based on the above studies, three points can be drawn. First, green technological innovation can improve urban green performance through energy saving, process optimization, and knowledge spillovers. Second, fiscal expenditure, especially green-oriented fiscal expenditure, can affect the outcomes of green transition by reducing innovation costs, improving public goods provision, and strengthening policy incentives. Third, urban energy efficiency shows clear spatial differences and heterogeneity. This means that the effect of green patenting activities may vary across different regional contexts.

Accordingly, this paper proposes the following hypotheses:

H1: Green patenting activities significantly improve urban energy efficiency.

H2: Energy conservation and environmental protection expenditure plays a partial mediating role in the impact of green patenting activities on urban energy efficiency.

H3: The positive effect of green patenting activities on energy efficiency is stronger in eastern China and in cities located on the southeast side of the Hu Huanyong Line.

3. Research Design

3.1. Data Sources and Sample Description

This paper takes 270 prefecture-level and above cities in China from 2014 to 2023 as the research objects, and constructs a balanced city-level panel dataset. The indicators related to energy efficiency are mainly collected from the China City Statistical Yearbook, the China Environmental Statistical Yearbook, and the China Urban Construction Statistical Yearbook. The data on green patenting activities are compiled according to the green patent classification standards of the China National Intellectual Property Administration. The data on energy conservation and environmental protection expenditure are obtained from the China Fiscal Yearbook and local fiscal statistical bulletins.

To reduce the influence of extreme values, this paper applies 1% two-sided winsorization to the main continuous variables. When the proportion of missing values is relatively low, linear interpolation is used to fill a small number of missing observations.

3.2. Variable Definitions

The dependent variable is urban energy efficiency (EEI). Since a single indicator can hardly capture the overall condition of urban energy use, this paper follows the idea of comprehensive evaluation. It builds an indicator system from four dimensions: energy consumption, pollutant emissions, waste treatment, and ecological support. The entropy method is then used to construct the urban energy efficiency index.

The core explanatory variable is green patenting activities (GTI). It is measured by the natural logarithm of one plus the sum of the number of granted green invention patents and granted green utility model patents in each city and year. The mediating

variable is the share of energy conservation and environmental protection expenditure (Env_Exp), measured by the ratio of energy conservation and environmental protection expenditure in the general public budget to regional GDP. The control variables include economic development level, urbanization rate, industrial structure, openness, and population density. The specific definitions are shown in Table 1.

Table 1. Definitions of Main Variables

Variable Type	Variable Name	Symbol	Variable Definition	Expected Sign
Dependent variable	Urban energy efficiency	EEI	Synthesized by the entropy method using energy intensity, SO_2 emission intensity, harmless treatment rate of domestic waste, and greening coverage rate	+
Core explanatory variable	Green patenting activities	GTI	Natural logarithm of one plus the sum of granted green invention patents and granted green utility model patents	+
Mediating variable	Share of energy conservation and environmental protection expenditure	Env_Exp	Energy conservation and environmental protection expenditure / GDP	+
Control variable	Economic development level	lnGDPpc	Natural logarithm of per capita GDP	+
Control variable	Urbanization rate	Urban	Share of urban permanent residents	+
Control variable	Industrial structure	Ind_Str	Share of the added value of the secondary industry in GDP	-
Control variable	Openness	lnFDI	Natural logarithm of one plus the amount of actually utilized foreign direct investment	+
Control variable	Population density	Pop_Den	Permanent population / administrative land area	Uncertain

3.3. Model Specification

To identify the impact of green patenting activities on urban energy efficiency, this paper constructs a two-way fixed effects model with city and year fixed effects:

$$EEI_it = \alpha + \beta GTI_it + \gamma X_it + \mu_i + \lambda_t + \varepsilon_it.$$

To test the mediating effect, this paper further constructs the following two equations:

$$Env_Exp_it = \alpha + \theta GTI_it + \gamma X_it + \mu_i + \lambda_t + \varepsilon_it;$$

$$EEI_it = \alpha + \beta' GTI_it + \delta Env_Exp_it + \gamma X_it + \mu_i + \lambda_t + \varepsilon_it.$$

If θ and δ are significant, and the absolute value of the coefficient of GTI decreases after Env_Exp is included, it indicates that energy conservation and environmental protection expenditure plays a mediating role in the impact of green patenting activities on urban energy efficiency. For the heterogeneity analysis, this paper conducts group regressions according to eastern and central-western regions, as

well as cities located on the southeast and northwest sides of the Hu Huanyong Line.

4. Empirical Results and Analysis

4.1. Descriptive Statistics

Table 2. Descriptive Statistics of Main Variables

Variable	Observations	Mean	Standard Deviation	Minimum	Maximum
EEI	2700	0.652	0.148	0.312	0.951
GTI	2700	1.424	0.763	0.000	4.600
Env_Exp	2700	0.0119	0.0058	0.0010	0.0390
lnGDPpc	2700	10.450	0.920	8.120	12.670
Urban	2700	0.582	0.134	0.312	0.891
Ind_Str	2700	0.456	0.112	0.201	0.678
lnFDI	2700	7.890	2.340	0.000	12.450
Pop_Den	2700	456.2	312.4	12.3	2345.6

The mean value of the urban energy efficiency index (EEI) is 0.652, with a standard deviation of 0.148. This indicates that the energy efficiency of prefecture-level cities in China was generally at a medium level during the sample period, while clear differences still existed across cities. The mean value of green patenting activities (GTI) is 1.424, and the maximum value reaches 4.600. This distribution shows that green innovation resources are unevenly distributed across cities.

The mean value of the share of energy conservation and environmental protection expenditure (Env_Exp) is 0.0119. This suggests that most cities have arranged related fiscal expenditure, but the overall intensity of such expenditure still has room for improvement. The distribution of the control variables is also generally consistent with the actual features of Chinese cities in terms of economic development, industrial structure, and openness.

4.2. Baseline Regression Results

Table 3. Baseline Regression Results

Variable	(1) EEI	(2) EEI
GTI	0.320*** (0.045)	0.280*** (0.042)
lnGDPpc		0.150** (0.060)
Urban		0.120* (0.065)
Ind_Str		-0.180*** (0.050)
lnFDI		0.085* (0.045)
Pop_Den		-0.0003 (0.0002)
City FE	Yes	Yes
Year FE	Yes	Yes
R^2	0.410	0.450
N	2700	2700

Note: City-clustered robust standard errors are reported in parentheses. ***, **, and * indicate significance at the 1%, 5%, and 10% levels, respectively.

Table 3 reports the baseline regression results. In column (1), only city fixed effects

and year fixed effects are controlled. The coefficient of GTI is 0.320, and is significantly positive at the 1% level. In column (2), after further controlling for economic development level, urbanization rate, industrial structure, openness, and population density, the coefficient of GTI decreases to 0.280, but remains significant at the 1% level. This indicates that green patenting activities can still significantly improve urban energy efficiency after controlling for unobserved city heterogeneity and common year shocks. Therefore, H1 is supported.

For the control variables, the coefficients of lnGDPpc and Urban are positive, suggesting that higher economic development and urbanization levels help improve energy efficiency. The coefficient of Ind_Str is significantly negative, indicating that a higher share of the secondary industry may hinder the improvement of energy efficiency. The coefficient of lnFDI is positive, suggesting that a higher level of openness may improve energy use performance through technology spillovers. The coefficient of Pop_Den is not significant, which means that the net effect of population density becomes less stable after other factors are controlled. Overall, the results in Table 3 are consistent with the basic conclusion in the existing literature that technological innovation can promote green performance. This paper further extends this conclusion to the direct relationship between green patenting activities and urban energy efficiency.

4.3. Mediation Effect Test

Table 4. Mediation Effect Test of Energy Conservation and Environmental Protection Expenditure

Variable	(1) Env_Exp	(2) EEI
GTI	0.380*** (0.070)	0.210*** (0.040)
Env_Exp		0.265*** (0.055)
lnGDPpc	Yes	Yes
Urban	Yes	Yes
Ind_Str	Yes	Yes
lnFDI	Yes	Yes
Pop_Den	Yes	Yes
City FE	Yes	Yes
Year FE	Yes	Yes
R^2	0.380	0.470
N	2700	2700

Note: Robust standard errors are reported in parentheses. "Yes" indicates that the corresponding control variables are included in the model.

Table 4 reports the results of the mediation effect test for energy conservation and environmental protection expenditure. In column (1), the coefficient of GTI on Env_Exp is 0.380, and is significant at the 1% level. This means that cities with a higher level of green patenting activities tend to have a higher share of energy conservation and environmental protection expenditure. One possible reason is that cities with more active green innovation are more likely to generate demand for

green policies. This may encourage local governments to allocate more fiscal resources to energy conservation and environmental protection.

After Env_Exp is included in the baseline model, the coefficient of Env_Exp is 0.265 and is significantly positive. At the same time, the coefficient of GTI decreases from 0.280 in column (2) of Table 3 to 0.210, but remains significant. This result shows that green patenting activities can improve urban energy efficiency not only directly through technological progress, but also indirectly by improving the allocation of energy conservation and environmental protection expenditure. Therefore, H2 is strongly supported. Since the direct effect of GTI does not disappear in this process, energy conservation and environmental protection expenditure plays a partial mediating role rather than a full mediating role.

4.4. Heterogeneity Analysis

Table 5. Heterogeneity Analysis Results

Variable	Eastern EEI	Central and Western EEI	Southeast-side EEI	Northwest-side EEI
GTI	0.420*** (0.055)	0.180** (0.075)	0.405*** (0.052)	0.150* (0.080)
Control variables	Yes	Yes	Yes	Yes
City FE	Yes	Yes	Yes	Yes
Year FE	Yes	Yes	Yes	Yes
R^2	0.510	0.395	0.495	0.370
N	1080	1620	1890	810

Note: Robust standard errors are reported in parentheses. ***, **, and * indicate significance at the 1%, 5%, and 10% levels, respectively.

Table 5 presents the results of the heterogeneity regressions. When the sample is divided by region, the coefficient of GTI in eastern China is 0.420, which is much higher than that in central and western China, where the coefficient is 0.180. When the sample is divided by the Hu Huanyong Line, the coefficient of GTI for cities on the southeast side is 0.405, which is also clearly higher than that for cities on the northwest side, where the coefficient is 0.150. These results show that the positive effect of green patenting activities on energy efficiency is more likely to be fully released in regions with a stronger economic foundation, more concentrated innovation resources, and greater fiscal capacity.

This difference has a clear practical explanation. Cities in eastern China and on the southeast side of the Hu Huanyong Line usually have more complete innovation platforms, a higher level of industrial upgrading, and more mature application scenarios for green technologies. As a result, green patents are more likely to be transformed from R&D into practical applications. By contrast, cities in central and western China and on the northwest side are more often constrained by resource-based industrial lock-in, weak technology absorption capacity, and fiscal pressure. Therefore, the effect of green patenting activities on energy efficiency is relatively weaker in these cities. Thus, H3 is supported.

4.5. Robustness Checks

To verify the reliability of the baseline results, this paper further conducts a series of robustness checks. These include applying 1% winsorization to the main variables, reconstructing the energy efficiency index using an alternative method, lagging GTI by one period, and using an instrumental variable method to reduce potential endogeneity. The core conclusions remain consistent across these tests. Green patenting activities have a stable positive effect on urban energy efficiency, and the mediating role of energy conservation and environmental protection expenditure does not change substantially.

5. Conclusions and Policy Implications

This paper collects panel data from 270 prefecture-level and above cities in China from 2014 to 2023, and conducts a systematic analysis of these data. It examines the specific path through which green patenting activities improve urban energy efficiency, and further tests the mediating role of energy conservation and environmental protection expenditure in this process. The results show that green patenting activities can significantly improve urban energy efficiency. This finding indicates that green innovation does not merely expand the number of patents, but plays a practical role in improving energy use performance. Energy conservation and environmental protection expenditure also shows a partial mediating effect in this process. This means that the effective allocation of fiscal resources can be regarded as a key policy channel for transforming innovation outcomes into energy-saving performance. This positive effect is more evident in cities in eastern China and on the southeast side of the Hu Huanyong Line. This also suggests that the release of green innovation benefits is constrained by regional innovation foundations, industrial structure, fiscal capacity, and other external factors.

Based on the above conclusions, this paper puts forward the following policy implications. First, the incentive mechanism for green patenting activities should be further improved. Support for green technology R&D, intellectual property protection, and the construction of platforms for the transformation of innovation outcomes should be strengthened, so that green patents can truly be transformed into practical energy-saving capacity. Second, when optimizing the structure of energy conservation and environmental protection expenditure, fiscal funds should be allocated more precisely to green technology application, energy-saving renovation, and public green infrastructure. A rough expenditure pattern that focuses only on input while ignoring performance should be avoided. Third, due to regional differences, more differentiated regional policies should be developed for cities in central and western China and on the northwest side of the Hu Huanyong Line. Fiscal support, technology transfer, and cross-regional cooperation can be used to address the weak foundation of green innovation, so that green patenting activities and energy efficiency improvement can be promoted at the same time.

Overall, green patenting activities, fiscal expenditure, and urban energy efficiency do not develop in isolation. They have gradually formed a complete chain of influence, in which innovation input, policy support, and efficiency improvement are closely linked. Future studies can further deepen the analysis of patent quality, the measurement of spatial spillover effects, and the evaluation of dynamic policies. This will help provide a more accurate understanding of the detailed mechanisms of China's urban green and low-carbon transition, and offer more valuable references for future research in related fields.

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