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Research article

The Impact of Urbanization on Energy Intensity — An Empirical Study on OECD Countries

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Abstract: With the significant increase in population and economic level, the link between urbanization and energy intensity in a nation has grown into a popular academic focus. In light of this, we explore the impact of urbanization on energy intensity by utilizing the differential GMM method. We take OECD countries as research samples and collect the panel data of 38 countries from 1990 to 2015. In addition, we discuss the moderating role played by innovation in the process of urbanization affecting energy intensity. The results are summarized as follows: first, in the current OECD countries, the effect of urbanization on energy intensity presents a significant inverted U shape, passing the robust test; second, heterogeneous impacts of urbanization on energy intensity are reflected by both the national developmental level and energy intensity; third, a higher innovation level causes a stronger inhibition effect of urbanization on energy intensity.

Keywords: urbanization level; energy intensity; inverted U-shape impact

JEL Codes: G15, F36, C40

1. Introduction

1.1. Research background

Energy intensity will be affected in the process of urbanization. Urbanization is an important indicator that reflects the development of countries. Economists regard a high level of urbanization as a success of economic development and economic transformation. In 1950, the world's urbanization level was only 29%; by 2008, it was over 50%. Developed countries have almost completed their urbanization with a high level exceeding 80%. They are now experiencing slow and stable urbanization, while developing countries are in the middle term of high-speed urbanization. However, with the increase of the urban population and the expansion of the city size, cities are now among the world's foremost contributors to energy consumption and greenhouse gas emissions. More and more pressure has been placed on natural resources and the ecological environment because urbanization needs both resource consumption and financial support. Energy is an indispensable natural resource for society as well as an essential foundation for economic development. Therefore, the high-speed urbanization inevitably enhances energy intensity. According to data statistics from Organization for Economic Co-operation and Development (OECD), cities consumed 60–80% of the world's energy, about the same proportion as carbon dioxide emissions (Naz et al., 2020; Zhao and Zhang, 2018). An et al. (2018) stressed that if this situation were not improved, urbanization would consume a lot of energy, leading to insufficient energy supply and ultimately inhibiting urbanization. Such problems are what economists call "growth resistance" to resource consumption in the process of urbanization. In the process of urbanization in developing countries, environmental pollution caused by primary energy consumption has also become a hot issue of global concern. In order to reduce the consumption of primary energy and curb the greenhouse effect, countries are also actively taking measures to reduce energy intensity and improve energy efficiency during urbanization. For instance, countries are committed to developing renewable energy sources to replace such primary energy consumption. Their goal is to increase the use of renewable energy by 43% between 2017 and 2022. This can not only prevent the risk of primary energy being exhausted but also reduce a large amount of energy consumption in the urbanization.

Urbanization takes effects on energy intensity from three dimensions. Firstly, different elements of urbanization affect energy use in different ways. Secondly, urbanization has complicated links with energy use due to the complexity of the process. Thirdly, urban policy interventions concerning the urbanization process could change energy use (Jeris and Nath, 2020; Madlener and Sunak, 2011; Wang et al., 2021; Zhong and Li, 2020). This eventually leads to a complex relationship between urbanization and energy intensity in countries with different levels of development, causing disagreements among scholars. Al-mulali et al. (2012) thought that there should be a significant long-term bidirectional relationship between urbanization and energy intensity, influenced by the national development level. When studying the relationship between energy intensity and urbanization in the low-, middle- and high-income countries, Al-mulali et al. (2013) found that urbanization reduces energy intensity in low-income countries while increasing it in high-income countries. They concluded that high-income countries should implement measures to improve energy efficiency as soon as possible. Hossain (2011) collected data from nine developing countries to analyze the relationship between urbanization and energy intensity. Empirical results verify the negative relationship between them. However, in the long run, urbanization may not damage the environment.

This paper explores the nonlinear relationship between urbanization and energy intensity based on a great deal of relevant literature. Alvarado et al. (2021) analyzed the link between urbanization and reduced consumption of non-renewable energy through an empirical study using linear and nonlinear models. Lin and Ouyang (2014) found a U-shaped relationship between energy demand and economic growth. In the early stage of urbanization, energy consumption increased in a direct proportion to the level of urbanization. However, when energy consumption reaches a peak, urbanization is correlated with improved energy efficiency. Lin and Zhu (2017) also studied the relationship between urbanization and energy intensity in 30 provinces in China from 2000 to 2015. According to the empirical results, urbanization and energy intensity showed an “inverted U-shaped” relationship. In light of the existing literature, we devote ourselves to discussing the complicated relationship between urbanization and energy intensity in this paper. We focus on the nonlinear relationship between them as the energy intensity varies with the level of urbanization. The data are collected from OECD countries from 1999 to 2015. Some countries in the OECD have become developed countries, so we compare the relationships between urbanization and energy intensity in countries developed before 1990 and some others that became developed after 1990 and are still developing.

1.2. Literature review and marginal contribution

To analyze the effect of urbanization on energy intensity, we found three channels transmitting the effect of urbanization on energy intensity based on the existing literature. Firstly, different elements of urbanization affect energy use in different ways. These elements involve architecture, environment, economic and industrial activities and social elements, and the like, belonging to city branches like residence, business, industry, and traffic, each of which consumes electricity, coal, and other fuels to meet social demand (Carreon and Worrell, 2018; Chiang, 2020; Li et al., 2021). Improving energy efficiency and strengthening the urban planning for energy use are beneficial to reducing the energy intensity (Sampaio et al., 2013). Chen and Chen (2015) summarized three methods of energy consumption accounting, quantifying the energy consumption of major components of a city. He also analyzed from the results how to sustainably utilize energy in urbanization. Pereira and de Assis (2013) thought it was important for cities to effectively plan their energy use to reduce energy intensity, which can help understand the relationship between the driving force of energy consumption and urban sectors. In the context of urban transformation, Fonseca and Schlueter (2015) introduced a comprehensive model to identify current and future changes in energy consumption in the residential, commercial and industrial sectors. He demonstrated the effect of urbanization and energy efficiency improvements by collecting data from some Swiss urban area. Collecting data from 30 China’s provinces from 2000 to 2015 as samples, Huo et al. (2021) used panel regression to explore the dynamic impact mechanism of urbanization on carbon dioxide emissions from the construction sector. The results indicate that urbanization promotes carbon dioxide emissions in the residential and construction sectors, but the degree of this effect is related to the difference in energy structure. If the energy intensity exceeds the critical value, i.e., a low energy efficiency, urbanization further enhances the carbon dioxide emission of urban residential buildings, showing the characteristic of “phased growth”. These indicate that urbanization can affect energy intensity from both direct and indirect channels.

Secondly, urbanization has complicated links with energy use due to the complexity of the process. Urbanization is a highly complex process. In the process of urbanization, the consumption of energy may be excessively wasteful. Urbanization includes economic process, social process, spatial process and technological process. For instance, in the economic process, urbanization represents a shift from a low energy-intensive agricultural society to a high energy-intensive urban society. As commercial, industrial, and manufacturing activities grow and cluster in cities, energy intensity will increase significantly. Improvements in energy efficiency could reduce the amount of energy wasted in this complex process. Liu (2009) pointed out that China should accelerate urbanization and reduce its reliance on energy-dependent industries while improving energy efficiency, which is the fundamental strategy to solve the dilemma of sustainable development between high energy intensity and urbanization. Sadorsky (2014) believed that industrial production relies heavily on intensive and large-scale energy sources in the current process of urbanization, resulting in high energy intensity. Using the autoregressive distributed lag co-integration test and Granger causality test, Shahbaz and Lean (2012) evaluated the relationships among energy consumption, financial development, economic growth and urbanization in Tunisia during 1971–2008. The results indicate that there is a long-term two-way causality among energy consumption, financial development and urbanization. Urbanization can use energy more efficiently and reduce energy intensity. Li and Lin (2015) considered the heterogeneous effect and "ratchet effect" regarding the random effects of population size, wealth level, and technology. They estimated the relationship between urbanization and energy intensity through different panel data. The results suggest that countries should improve energy efficiency when promoting urbanization from the perspective of economic process and social process. Fernandez et al. (2018) provided insights on improving the industrial level in urbanization through energy efficiency on the premise of improving technology. Therefore, the complex process of urbanization has a significant impact on energy intensity.

Thirdly, urban policy interventions concerning the urbanization process could change the course of energy use. Urbanization policies can affect the link between urbanization and energy use. Different policies of urbanization play an essential role in reducing energy intensity (Bernardini and Galli, 1993; Li et al., 2020; Utomo et al., 2020). Besides, areas with a high level of urbanization often have more efficient governance controlling energy consumption. In his empirical analysis, Jiang and Lin (2012) mentioned that the relationship between China's energy intensity and urbanization is inverted U-shaped, which can be reshaped by urban energy use policies. This reflects the significant importance of policies formulated by the Chinese government in the relationship between urbanization and energy intensity. Lv et al. (2019) studied the effect of urbanization on energy consumption in response to regional policies by collecting time-series data related to energy and urbanization from 1997 to 2016 and using integrated spatial panel data modeling and interactive effect modeling. Irfan and Shaw (2017) examined the relationships among environmental pollution, energy consumption, and urbanization level in India, Pakistan, and Bangladesh from 1978 to 2011. The results suggest that energy consumption levels in cities vary with the policies implemented. Countries should formulate appropriate policies to promote urbanization, reduce energy intensity and protect the environment. Chiang (2020) and Pan et al. (2021) mentioned in their paper that the New Energy Demonstration City Policy (NEDC) is of great significance to promoting the sustainable development of China's energy. They analyzed the energy use in cities with different urbanization levels by collecting the data of 271 cities in China from 2005 to 2016 and using the difference-in-differences method and the mediation model. The results suggest that NEDC significantly improves energy efficiency. Meanwhile, the relationship is heterogeneous among cities with different levels of urbanization. This provides ideas for promoting new energy demonstration cities and the deep development of new energy technologies. Accordingly, the implementation of urban policies has a greater impact on energy intensity.

Many methods and ideas in the existing literature can be learned from when working on the effect of urbanization on energy intensity. However, it is hard to define their relationship clearly. First, most studies only test their linear relationship. Second, some focus on the heterogeneous effects of urbanization on the energy intensity differentiated by zones, leading to a single partition criterion. Third, when exploring the relationship between energy intensity and urbanization, little attention is paid to how other factors influence the effect of urbanization on energy intensity. Based on the existing research, this paper uses the data of OECD countries from 1990 to 2015 to explore the nonlinear impact of urbanization on energy intensity. It can enrich the research topic in this field. Compared with the existing literature, the current paper performs the following three improvements. First, we explore the nonlinear relationship between energy intensity and urbanization by applying the differential Generalized Method of Moments (GMM) to take an empirical analysis. GMM is beneficial for us to observe the non-linear impact between the urbanization and energy intensity, as well as reduce the error of the intergroup heteroscedasticity that affects the experimental results in the panel data. In addition, the robust test is addressed by selecting another indicator for energy intensity. Second, we analyze the heterogeneity of the impact of urbanization on energy intensity in terms of development levels and energy intensity. We also discuss the reasons for such a difference. Third, we test the moderating role of the innovation level in the effect of urbanization on energy intensity by constructing a model involving interaction terms.

The rest of the paper can be organized as follows. Section 2 sets forth the research scheme, involving theoretical analysis, research hypotheses, model setting, variable selection, and data sources. Section 3 tests the regression for the effect of urbanization on energy intensity, involving the robustness test. Section 4 analyzes the heterogeneity mechanism. Section 5 concludes the research and proposes some policy suggestions.

2. Materials and methods

2.1. Theoretical analysis and research hypotheses

The direct impact of urbanization on energy intensity is the main reason for the complex relationship between them. Some scholars believe that urbanization increases energy intensity. According to the data provided by the U.N. Environment Programme in 2012, cities and towns account for 3% of the global area but consume 75% of the natural resources, such that they account for 60%–80% of the total greenhouse gas emissions (Elliott et al., 2017; Gorelick and Walmsley, 2020; Li and Liao, 2020; Li et al., 2019; Zheng et al., 2020). Jones (2004) showed that the increase in energy consumption is not only related to per capita income and industrial structure but also closely related to urbanization. York (2007) and Rafiq et al. (2016) took 14 E.U. countries and 22 emerging countries as samples, respectively, and they concluded that urbanization has a significantly positive impact on energy intensity. However, through empirical analysis, some other scholars found that urbanization would directly and negatively impact energy intensity under certain conditions. Martínez-Zarzoso and Maruotti (2011) found an inverted U-shaped relationship between urbanization and carbon dioxide emissions. Urbanization level has a threshold effect. If the threshold is exceeded, the impact of urbanization on carbon dioxide emissions will not increase further, nor will energy intensity increase further. Other scholars believed that the impact of urbanization on energy intensity varies with a country's development level. Using samples of nine Pacific island countries, Mishra et al. (2009) found differences in the impact of urbanization on energy, where the root cause is the different levels of development among countries. Poumanyvong and Kaneko (2010), classifying countries by per capita income, found that urbanization has a negative impact on energy use in low-income countries but a positive impact on middle- and high-income countries. In light of the above studies, this paper argues that there should be a nonlinear relationship between urbanization and energy intensity. So we propose the following hypothesis and take empirical tests.

Hypothesis 1: *The impact of urbanization on energy intensity is an inverted U shape.*

Whether there is a difference in the effects of urbanization on energy intensity concerning different levels of national development is a crucial point of discussion in this paper. This paper uses panel data from OECD countries to discuss the effect of urbanization on energy intensity. In light of this, this paper divides the OECD countries into two classes (early developed countries and other countries) to explore whether differences in national development levels lead to different effects taken by urbanization on the energy intensity. Al-Mulali et al. (2015) classified 129 countries by income levels to explore the differences in the impact of urbanization on carbon dioxide emissions. The increase in carbon dioxide emissions is mainly dependent on the increase in energy consumption. As an influencing factor, urbanization plays different roles in countries with different levels of development, resulting in differences in energy consumption levels. In this paper, we put forward Hypothesis 2 to explore the difference in the effect of urbanization on energy intensity with respect to different development levels of countries.

Hypothesis 2: *The impact of urbanization on energy intensity is heterogeneous with respect to early developed countries and other countries.*

Is it different in the effects of urbanization on energy intensity? This is what is concerned in this paper. Zhang and Lin (2012) collected provincial panel data in China to study differences in energy intensity among different provinces. They found differences in the effects of urbanization on both energy consumption and carbon dioxide emissions. In OECD, the different geographical locations, industrial productions and economic levels of countries lead to the prominent energy intensity of some countries. In light of this, in this paper, we propose Hypothesis 3 to explore the heterogeneity in the effect of urbanization on different energy intensities.

Hypothesis 3: *The energy intensity makes differences to the effects of urbanization on energy intensity.*

Based on the established relationship between urbanization and energy intensity, this paper discusses some factors influencing the effect of urbanization on energy intensity. Innovation can promote urbanization, and it can also synergistically promote economic development through interactive ways. Moreover, the decline in energy intensity cannot be achieved without innovation in energy technology. Accordingly, this paper selects innovation level as a moderating variable to explore its effect on this relationship. Taking 36 OECD countries as examples, Koksal et al. (2021) collected data from 1990 to 2017 to explore whether the financial system's demand for renewable energy is significant. They found that the whole financial system has a significant impact on the demand for renewable energy. In particular, as a part of the financial system, the promotion of urbanization relies heavily on renewable energy development. As renewable energy development depends on the degree of technological innovation, they put forward policy recommendations on technological innovation. Therefore, innovation level was selected as the moderating variable in this paper to verify Hypothesis 4.

Hypothesis 4: *Innovation level plays the role of moderating effect in linking urbanization to energy intensity.*

2.2. Models setting

This paper aims to discuss the relationship between urbanization and energy intensity. In addition, the existing literature has implied the nonlinear relation between them. Thus, model (1) is used to test Hypothesis 1. To keep the robustness, we set Model (2) to compare the results with Model (1). In the models, i represents the country; t represents the year; j represents the indicator of control variable *Control*; α and β represent the regression coefficients; ε and ε' represent the random errors.

$$lneu_{it} = \alpha_0 + \alpha_1 * urban_{it}^2 + \alpha_2 * urban_{it} + \sum_{j=3}^{7} \alpha_j * Control_{it} + \varepsilon_{it} \quad (1)$$

$$lneil_{it} = \beta_0 + \beta_1 * urban_{it}^2 + \beta_2 * urban_{it} + \sum_{j=3}^{7} \beta_j * Control_{it} + \varepsilon'_{it} \quad (2)$$

This paper follows the moderating regression analysis method from Toothaker (1994) by setting Model (3) to test Hypothesis 4, where *adj* represents the moderating variable. For testing the role of innovation level in linking urbanization to energy intensity, we add the product of urbanization and innovation level, investigating their interaction and measuring the crowding-out effect of innovation level.

$$lneu_{it} = \gamma_0 + \gamma_1 * urban_{it} + \gamma_2 * adj_{it} + \gamma_3 * urban_{it} * adj_{it} + \sum_{i=4}^{7} \gamma_i * Control_{it} + \theta_{it} \quad (3)$$

2.3. Variable selection and data sources

Based on previous studies, this paper selects some relevant indicators to explore the relationship between urbanization and energy intensity, and distinguishes developed countries before 1990 from other countries. The introduction of relevant indicators is shown in Table 1.

Table 1. Variable selection.

	Primary indicator	Abbreviation	Secondary indicator
Explained variable	Energy intensity	eil	Energy intensity level of primary energy
		eu	Energy consumed per 1000 US dollars of GDP
Explanatory variable	Urbanization	urban	Annual growth rate of Urbanization
Control variable	Carbon dioxide intensity	CO_2	Carbon dioxide produced by crude oil per 1kg of energy consumption
	economic growth	gdp	Annual GDP growth rate
	Industrialization level	industry	Annual growth rate of industrial added value
	Openness	exports	Annual growth rate of exports of goods and services
Moderating variable	Innovation level	patent	Number of patent applications

Notes: The data are all from World Development Indicators from 1990 to 2015 in the World Bank database, and the missing data have been completed with linear interpolation.

In this paper, the energy intensity of primary energy (eil) is selected as the measurement indicator of energy intensity because most countries consume a large proportion of primary energy in the current process of energy consumption. Renewable energy is still in the development stage and cannot provide sufficient support for national development. Therefore, this paper uses primary energy intensity to measure energy intensity.

The energy consumed per 1000 US dollars of GDP (EU) represents the share of energy consumed by each country in GDP. It reflects how energy intensity changes with the improvement of economic development level.

The annual growth rate of urbanization (urban) can reflect the situation of population migration to cities, urban expansion and urban economic growth. It represents the urbanization level of a country.

Carbon dioxide produced by crude oil per 1kg of energy consumption (CO_2) represents the intensity of carbon dioxide produced by energy consumption. If its level is too high, it means that the national energy intensity is high. In order to prevent serious harm to the environment, the use of energy should be reduced.

The annual growth rate of GDP (GDP) reflects the impact of a country's economic level on energy intensity. Rapid economic growth may require a lot of energy support, which is highly dependent on energy intensity.

The annual growth rate of industrial added value (industry) reflects the impact of industrial level on energy intensity. Because industrialization consumes a large proportion of energy, it has a significant impact on energy intensity.

The annual growth rate of exports of goods and services (exports) represents the effect of national openness on energy intensity. Because energy is a commodity, it can not only be used at home, but also be traded to other countries.

When exploring whether there is a moderating effect in the process of urbanization affecting energy intensity, this paper needs to choose a moderating variable for empirical analysis to observe whether it can affect the effect of urbanization on energy intensity. By referring to Dauda et al. (2021), who explored the inverted U-shaped relationship between the impact of innovation level on carbon dioxide in some African countries, this paper uses innovation level as a moderating variable to analyze how it affects the effect of urbanization on energy intensity. On the one hand, there is a certain degree of correlation between innovation level and energy intensity. The improvement of a country's innovation capacity, which is of great help to the reduction of primary energy consumption and the development of renewable energy, can directly affect energy intensity. On the other hand, the improvement of innovation ability can promote urbanization. The city's economic level, industrial structure and industrial level will develop well with the increase of innovation level. Therefore, innovation level is selected as the moderating variable in this paper.

Table 2. Descriptive analysis.

VarName	Obs	Mean	SD	Min	Median	Max	Skewness	Kurtosis
lneu	1140	4.684	0.363	3.679	4.715	5.950	0.472	3.446
lneil	1140	1.655	0.365	0.667	1.657	2.956	0.133	0.612
up	1140	0.909	1.015	–2.800	0.830	6.130	0.316	4.579
gdp	1140	2.763	3.090	–14.839	2.763	25.163	–0.411	9.091
industry	1140	2.318	5.035	–24.857	2.318	75.056	2.080	43.836
$LnCO_2$	1140	0.778	0.321	–1.131	0.820	1.291	–2.152	10.932
exports	1140	44.637	27.554	8.972	37.778	221.197	2.687	14.053
lnpatent	1140	8.129	2.156	3.091	7.957	13.340	0.210	2.695

The data of OECD countries are used from World Development Indicators in DataBank. After considering the availability and validity of the data, this paper decides to use the data from 1990 to

2015. In order to avoid errors in the empirical results caused by inconsistent units, the energy intensity level of primary energy (eil), Carbon dioxide produced by crude oil per 1kg of energy consumption (CO_2) and the number of patent applications (patent) are logarithmically treated, and the other indicators remain unchanged. The descriptive statistics of various indicators involved in this paper are shown in Table 2. For each variable, we present the Mean, standard deviation (Std. SD.), minimum (Min), Median, maximum (Max), Skewness and Kurtosis. We concentrate on lneu, lneil and up. The lneu ranges from 3.679 to 5.950. And the lneil ranges from 0.677 to 2.956. They both are right-skewed distribution but their distributions of kurtosis are different. The up ranges from –2.800 to 6.130. It is the distribution of right-skewed and high kurtosis.

3. Results

The panel data of OECD countries from 1990 to 2015 are used to make differential GMM estimation of Model (1) with Stata16.0 software. The samples selected in this paper have the characteristics of large sample size and short time span (N is large and T is small), so using the differential GMM method to estimate the model can ensure the accuracy of the regression results. In addition, differential GMM can effectively solve the endogeneity problem. There are two reasons for generating endogeneity in this study. First, there are missing variables that affect urbanization and energy intensity simultaneously. That is, there is no causal relationship between urbanization and energy intensity, but a certain missing variable affects urbanization and energy intensity. Second, there is a reverse causal relationship between urbanization and energy intensity, that is, changes in energy intensity will also lead to changes in urbanization level. Due to these two reasons, endogeneity problems will occur, which will bias the regression results, and the least squares method (OLS) requires strict exogeneity between variables, so this paper uses the differential GMM method to set instrumental variables for empirical analysis. The empirical results are shown in Table 3.

The results in Table 3 show a significant inverted U-shaped relationship between urbanization and energy intensity; that is, urbanization first promotes energy intensity and then inhibits it. In Table 3, the coefficient of the quadratic term of urbanization is –0.035, which is significant at the level of 0.01. The coefficient of the first-order term of urbanization is 0.164, and it is significant at the level of 0.05. The results indicate that the impact of urbanization on energy intensity is inverted U-shaped; that is, the improvement of urbanization level will promote energy intensity at first, and after a period of development, the increase of urbanization will suppress energy intensity after reaching the peak of energy intensity. So, Hypothesis 1 is confirmed. Moreover, the results in Table 3 also show that carbon dioxide emission and one-phase lag of energy intensity have a significant positive impact on energy intensity; the level of industrialization and openness have a significant negative impact on energy intensity, and the impact of economic growth on energy intensity is not significant. This situation may be due to the phased differences in the demand for energy intensity in urbanization. In the initial stage of urbanization, a country's economic development, industrial level and population concentration need strong support from energy, which leads to a large demand for energy in the process of urbanization. In this stage, the country will consume a large amount of energy to promote urbanization, leading to a significant increase in energy intensity. However, with the increase of urbanization in various countries, especially in many developed countries whose urbanization level has reached more than 80% and urbanization strategies are stable and gradual, they do not need to consume a large amount of energy to improve their urbanization level.

Table 3. Regression results.

	Diff-GMM lneu	Diff-GMM lneil
L.lneu	0.692***	
	(8.398)	
L.lneil		0.859***
		(31.088)
up	0.164**	0.011*
	(2.419)	(1.684)
up^2	–0.035***	–0.004***
	(–3.174)	(–3.185)
gdp	0.006	–0.005***
	(1.014)	(–5.256)
industry	–0.009***	0.001
	(–2.801)	(1.055)
$LnCO_2$	0.578***	–0.067
	(2.975)	(–1.597)
exports	–0.015***	–0.001
	(–2.785)	(–1.198)
Time effect	YES	YES
_cons	–20.320***	0.316***
	(–3.601)	(6.123)
N	1064	1064

Notes: * p<1, ** p<0.05, *** p<0.01.

In addition, due to a large amount of energy consumption in the early stage of urbanization, some adverse effects on the urban environment have been caused. At this time, countries have put forward measures to improve energy efficiency. On the one hand, these measures can protect the environment and curb the greenhouse effect. On the other hand, the effect of environmental degradation on economic growth is inverted U-shaped; that is, if energy intensity continues to increase, the economy of each country will be inhibited to a certain extent (Li et al., 2021; Li et al., 2021; Ozturk et al., 2016). According to the Environmental Kuznets Curve (EKC) hypothesis, economic growth increases with the increase of carbon emissions, and when the development reaches a particular stage, the increase of carbon emissions will inhibit economic growth. The biggest source of carbon emissions is energy consumption, especially the consumption of non-renewable energy, and there is a directly proportional relationship between the two. Therefore, countries attach great importance to the reduction of energy intensity and the development of renewable energy. Anis's research suggests that, according to the EKC hypothesis, there may be an inverted U-shaped relationship between energy intensity and carbon dioxide emissions; that is, energy intensity increases and then decreases. Energy intensity is also closely related to economic growth because when energy intensity is high, the economy also grows. However, consistent with the above relationship, they are in an inverted U-shaped relationship. In the later stage, if energy use efficiency increases, the economic level will continue to grow and the urbanization will be better promoted (Li et al., 2021; Omri, 2013).

In order to ensure the accuracy of the research results, this paper selects the energy intensity of primary energy (eil), which has a strong correlation with the energy consumed per 1000 US dollars of

GDP, to measure energy intensity and conducts robustness tests on the empirical results. The results in Table 1 show that the quadratic coefficient of urbanization on the energy intensity of primary energy is significantly negative, while the first-order coefficient is significantly positive. This indicates that there is also a significant inverted U-shaped relationship between urbanization and the energy intensity of primary energy. Therefore, the empirical results are robust.

4. Further discussions

4.1. Heterogeneity test

According to the different development levels of OECD countries, this paper divides them into two categories based on the boundary of 1990, namely early developed countries and other countries[1], to study whether there is a difference in the impact of urbanization on energy intensity between early developed countries and other countries. Moreover, this paper selects the energy intensity in the 50% quantile of OECD countries (energy intensity = 111.5704) to explore whether there are differences in the impact of urbanization on energy intensity at different levels. The empirical results are shown in Table 4.

Table 4. Heterogeneity test results.

	Other countries lneu	Early developed countries lneu	Energy intensity (< 111.5704) lneu	Energy intensity (≥ 111.5704) lneu
up	–0.067***	–0.020**	–0.013	–0.036*
	(–2.621)	(–2.350)	(–1.544)	(–1.830)
gdp	–0.004	0.001	0.003	–0.007*
	(–0.856)	(0.461)	(1.120)	(–1.666)
industry	0.001	–0.003*	–0.004***	0.003
	(0.469)	(–1.930)	(–3.269)	(1.295)
$lnCO_2$	0.080	–0.403***	0.020	–0.248***
	(0.464)	(–5.909)	(0.345)	(–3.845)
exports	–0.001	–0.003***	–0.003***	0.001
	(–0.782)	(–4.918)	(–5.416)	(1.407)
Time effect	YES	YES	YES	YES
Individual effect	YES	YES	YES	YES
_cons	4.623***	5.924***	4.772***	5.315***
	(21.791)	(31.303)	(74.020)	(64.614)
N	390	598	570	570

Note: * p<1, ** p<0.05, *** p<0.01.

1Countries that became developed countries before 1990 include the United States, Britain, France, Germany, Italy, Canada, Ireland, the Netherlands, Belgium, Luxembourg, Austria, Switzerland, Norway, Iceland, Denmark, Sweden, Spain, Portugal, Greece, Japan, Finland, Australia and New Zealand; Countries that did not become developed countries before 1990 include Turkey, Mexico, the Czech Republic, Hungary, Poland, South Korea, Slovakia, Chile, Slovenia, Estonia, Israel, Latvia, Lithuania, Colombia and Costa Rica.

The results in Table 4 show that the heterogeneity of urbanization to energy intensity is reflected in two aspects: different development levels and different energy intensity among countries. The empirical results show that urbanization impacts energy intensity, but the degrees of impact are different with different national development levels. Compared with early developed countries, urbanization in other countries has a significantly greater restraining effect on energy intensity. So Hypothesis 2 is confirmed. The reason may be the difference in the level of urbanization between early developed countries and other countries, as well as the different periods in which urbanization is promoted (Bilgili et al., 2017; Li et al., 2021). Since the urbanization level of early developed countries has reached saturation, they have started to implement the urbanization policy of stable development. However, these countries used to rely heavily on energy, and the process of urbanization almost depended on a large amount of energy consumption. In the early stage, science and technology could not promote urbanization on the premise of improving energy efficiency, so urbanization had little inhibitory effect on energy intensity in these countries. In other countries, there are problems such as weak production capacity, an underdeveloped economy and a low degree of scientific and technological innovation, which makes it late for them to improve urbanization. At present, other countries are still committed to promoting high-speed urbanization (Li et al., 2020; Sadorsky, 2013). However, with the improvement of the current scientific and technological level, other countries no longer improve the urbanization level on the premise of consuming a large amount of energy but promote the urbanization by improving energy efficiency and developing renewable energy, which can not only protect the ecological environment but also provide better help for economic development. Therefore, this paper believes that the inconsistent urbanization level and different development stages between early developed countries and other countries are the main reasons for the heterogeneity in the impact of urbanization on energy intensity.

The empirical results also show that the impact of urbanization on energy intensity is significantly different under different degrees of energy intensity. In countries with energy intensity less than 111.5704, the influence coefficient of urbanization on energy intensity is –0.013 but not significant, indicating that urbanization is not the main factor affecting energy intensity. In countries with energy intensity greater than or equal to 111.5704, the influence coefficient of urbanization on energy intensity is –0.36 and significant at the level of 0.1, indicating that urbanization will significantly inhibit the increase of energy intensity. So Hypothesis 3 is confirmed. The reason for this may be differences in energy dependence among countries. For energy-intensive countries, they have relied too much on energy use in the process of urbanization. In order to prevent the destruction of ecological environment and the obstruction of economic development, these countries need to take adequate measures to reduce the increase of pollution emissions caused by the transformation of industrial structure and energy consumption structure in the process of urbanization. Therefore, urbanization will have a negative impact on energy intensity in these countries. For countries with low energy intensity, their urbanization is not highly dependent on energy, and its impact on energy intensity is not apparent. In the process of urbanization, these countries do not need a large amount of energy to improve the level of urbanization. Instead, they promote urbanization by improving industrial structure. Therefore, the energy demand is small in the process of urbanization, and the impact of urbanization on energy intensity is not significant. It is also possible that the development level of these countries is not high, and affected by factors like geographical location and resource endowment they do not have enough energy to support their urbanization. Their energy supply is also low in the process of urbanization, so urbanization cannot affect energy intensity.

4.2. Moderating effect analysis

In order to explore whether innovation can affect the effect of urbanization on energy intensity, this paper uses innovation level as a moderating variable to conduct an empirical analysis. The empirical results are shown in Table 5.

Table 5. Results of moderating effect analysis.

	OLS	Moderating effect
	lneu	lneu
up	–0.057***	–0.216***
	(–4.388)	(–4.667)
up*lnpatent		0.020***
		(3.682)
gdp	–0.003	–0.004
	(–1.008)	(–1.077)
industry	–0.000	–0.000
	(–0.166)	(–0.088)
$lnCO_2$	–0.329***	–0.309***
	(–5.131)	(–5.137)
exports	–0.002***	–0.001**
	(–2.740)	(–2.042)
lnpatent	–0.004	–0.014
	(–0.424)	(–1.439)
Time effect	YES	YES
Individual effect	YES	YES
_cons	5.576***	5.578***
	(41.282)	(39.621)
N	1140	1140

Note: * p<1, ** p<0.05, *** p<0.01.

According to the results in Table 5, the increase of innovation level will intensify the restraining effect of urbanization on energy intensity. The OLS regression results in Table 5 show that, urbanization has a negative impact on energy intensity with a coefficient of –0.057 and is significant at the level of 0.01, indicating that urbanization has a restraining effect on energy intensity. When the innovation level is added, the empirical results show that the interaction term between urbanization and innovation level is positive, with a coefficient of 0.02 and significant at the level of 0.01. After adding interaction term, the impact of urbanization on energy intensity is still negative and significant, but the negative impact is significantly improved, indicating that the increase of innovation level can enhance the negative impact of urbanization on energy intensity to some extent. This may be because innovation has changed the development trend of urbanization. In the past urbanization process, energy has provided continuous support for urbanization, which is a vital part of urbanization. However, with the development of science and technology, countries find that innovation can effectively improve the level of urbanization and avoid the negative externalities caused by large amounts of energy consumption. In particular, in the process of urbanization affecting energy intensity, innovation level has a crowding-out effect on the process, exacerbating the negative impact of urbanization on energy intensity (Ji and Chen, 2017; Li et al., 2021; Yang et al., 2021). Innovation is considered to be an effective tool to promote the high-quality development of society because, on the one hand, it can reduce carbon dioxide emissions, promote the upgrading of industrial structure, increase human capital, improve education development, and generate a positive impact on comprehensive factors such as infrastructure and culture. The improvement and perfection of these factors are closely related to the process of urbanization, and they can promote the construction of urbanization more effectively. On the other hand, innovation plays a significant role in environmental protection. Countries are improving energy efficiency and reducing energy intensity through innovation in clean energy. Therefore, to a certain extent, innovation can reduce energy consumption and avoid energy waste and excessive energy intensity in the process of urbanization. The relationship between innovation level and urbanization is not just a simple one-way relationship. According to the spatial economic growth theory, the development of urbanization can provide necessary human capital, capital and development space for regional technological innovation, and urbanization can also create many scientific and technological needs (Liu et al., 2020; Pablo-Romero and Sanchez-Braza, 2017). Therefore, this paper believes that innovation can affect the effect of urbanization on energy intensity.

5. Conclusions

Based on dynamic panel data of OECD countries from 1990 to 2015, this paper explores the impact of urbanization on energy intensity under the premise of controlling the impact of various factors on energy intensity. Compared with theoretical analysis, this paper focuses on empirical analysis results. First, this paper explores the impact of urbanization on energy intensity with a differential GMM model. Secondly, this paper discusses the differences in the impact of urbanization on energy intensity in terms of development level and energy intensity degree through the heterogeneity test. Finally, this paper takes the level of innovation as a moderating variable to explore its moderating effect in the process of urbanization affecting energy intensity.

The empirical results show that: first, in the current OECD countries, there is a significant inverted U-shape impact of urbanization on energy intensity, and the empirical results are robust. Due to the phased differences in the demand for energy intensity in urbanization, with the improvement of urbanization, energy intensity will increase first and then decrease. It shows that the demand of energy intensity varies with the different stages of urbanization, and the primary stage of urbanization needs to rely on a large amount of energy as support. When urbanization develops to a certain level, the demand for energy decreases. The main policy proposal of the paper might be that OECD countries might need to implement policies considering energy efficiency in the urbanization and development processes. After countries achieving a certain level of urbanization, these policies should mitigate energy demand stemming from the urbanization process.

Second, the heterogeneity of urbanization on energy intensity is reflected in national development and energy intensity degrees. Due to the different levels and development stages of urbanization, the inhibition effect of urbanization in early developed countries on energy intensity is less than that in other countries. And because the country’s dependence on energy is inconsistent, resulting in different energy intensity degrees, the impact of urbanization on energy intensity is heterogeneous. For countries with high energy intensity, urbanization has a significant inhibitory effect on energy intensity. For countries with low energy intensity, urbanization will not significantly affect energy intensity. Therefore, countries with the lower level of urbanization need to implement some relevant policies on energy conservation and emission reduction. They prohibit to increase energy pollution while raising the level of urbanization. In the process of steadily promoting urbanization, countries with the higher level of urbanization make use of clean energy and other pollution-free resources to reduce energy pollution.

Third, the improvement of innovation level will enhance the inhibitory effect of urbanization on energy intensity. The empirical results show that innovation has a moderating effect in the process of urbanization affecting energy intensity, because innovation can better improve the process of urbanization and reduce the energy pollution generated by cities. In order to protect the ecological environment and prevent excessive energy consumption which hinders the development of urbanization, the state should actively encourage innovation. In this way, the countries can not only improve the national level of innovation, but also develop the urbanization while protecting the environment.

Based on the above conclusions, this paper puts forward the following targeted suggestions. First, countries should determine energy use according to the level of urbanization. According to the empirical results, there is a significant inverted U-shape impact of urbanization on energy intensity. This shows that countries need to consume a large amount of energy in the initial stage of urbanization, but after urbanization reaches a certain level, it will not increase energy intensity anymore. In this stage, the improvement of energy efficiency in various countries will not only promote the rapid development of urbanization, but also promote the reduction of energy intensity. Therefore, it is reasonable to determine energy consumption according to the urbanization level.

Second, countries at different stages of development need to implement different and reasonable policies to promote urbanization. Due to different urbanization levels in developed and developing countries, there are also differences in energy intensity (Li et al., 2020; Liu et al., 2020; Wang et al., 2020). Nowadays, most OECD countries have become developed countries, and the urbanization rate has reached about 80%, and urbanization in these countries has entered a stage of steady development, so it does not need to improve the urbanization level at the cost of a large amount of energy. If developed countries continue to invest large amounts of energy in the process of urbanization, this could lead to a stronger greenhouse effect and slower economic growth. Therefore, based on maintaining the current energy intensity, developed countries should minimize energy use and promote urbanization in an all-round way through other aspects. For developing countries, because urbanization has not reached a high level, urbanization still needs strong support from energy. However, it does not mean that developing countries should continue to invest more energy; instead, they should improve energy efficiency on the premise of not increasing energy consumption. On the one hand, urbanization in developing countries can be raised to the same level as that in developed countries; on the other hand, they should protect the environment and curb the greenhouse effect.

Third, countries should continue to improve the level of innovation. The empirical results show that the level of innovation will improve the negative impact of urbanization on energy intensity. It can also improve the level of urbanization from many aspects, such as optimizing the industrial structure, reducing industrial pollution and enhancing the level of industrial development. Therefore, it is worthwhile for countries to invest a lot of resources to improve the level of innovation. Liobikiene et al. used panel data from 147 countries from 1990 to 2012 and the systematic GMM method to conduct empirical tests. They explored the relationship between economic growth, urbanization, technological innovation and the greenhouse effect. The empirical results show that if countries want to promote economic growth and urbanization further, they should proceed on the premise of a higher level of innovation (Li and Zhong, 2020; Liobikiene and Butkus, 2019).

Based on the above analysis, this paper argues that there are improvements for research on the relationship between urbanization and energy. First, based on the data of OECD countries, this paper explores the nonlinear impact of urbanization on energy intensity, but this only represents the situation of OECD countries. The relationship between urbanization and energy intensity may be different for developing countries with high development level such as China. It is more convincing to expand this research method to other countries for comparison. Second, this paper divides developed countries and developing countries according to 1990, but some countries also become developed countries in the following years. The improvement for further improvement in the division standard. The limitations of this paper are the estimation method is not novel. Due to the availability of data, the latest data can't be obtained. Only one factor affecting urbanization as an energy intensity process is found. These limitations are worth solving and continuing to explore in depth.

Conflict of interest

All authors declare no conflicts of interest in this paper.

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