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Threshold Effect of Economic Growth on Energy Intensity—Evidence from 21 Developed Countries

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Abstract: Based on threshold regression models, this paper analyzes the effect of economic growth on energy intensity by using panel data from 21 developed countries from 1996 to 2015. Results show that a 1% increase in GDP per capita can lead to a 0.62–0.78% reduction in energy intensity, implying economic growth can significantly reduce energy intensity. The extent of the reduction in energy intensity varies depending on the economic development stages represented by key influencing factors including energy mix in consumption, urbanization, industrial structure, and technological progress. Specifically, the reduction in energy intensity due to economic growth can be enhanced with relatively more renewable energy consumption and more urban population until a threshold point, where the enhancement disappears. On the other hand, the extent of the energy intensity reduction due to economic growth can be weakened with relatively more tertiary industry activities and more research and development (R&D) investment in an economy until a threshold point, where the weakening cannot continue. However, compared to the early stages represented by the low ends of renewable energy consumption, urban population, tertiary industry activities, and R&D investment, the later stages represented by the high ends of these key factors after a threshold show the weakened effect of economic growth on the decline of energy intensity. Hence, when an economy is well-developed, policy makers are advised to put fewer expectations on the role of economic growth to reduce energy intensity, while pursuing relatively cleaner energy, greater urbanization, more tertiary industry activities, and advanced technologies.

Keywords: economic growth; energy intensity; threshold regression; renewable energy; urbanization; industrial structure; R&D investment

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1. Introduction

Energy is one of the key driving forces for sustainable economic development. In the face of resource depletion and environmental carrying-capacity limits, reducing energy input while keeping economic growth is important for sustainable development in economic, social, and environmental fields. With the aggravation of the contradiction between energy demand and the prominent pressure of environmental protection, the appeal for energy conservation and emission reduction is increasingly higher, and the pursuit of green and sustainable economic development has become the goal of almost all countries.

According to BP's "Statistical Review of World Energy 2020" [1], coal is still the largest source of power generation in the world, accounting for 36% of global power generation in 2019; the growth of carbon emissions has slowed but is still high. In the process of the world's transition to sustainable green and low-carbon development, it is difficult for the global energy system to eliminate its dependence on fossil energy in the short term. Although traditional energy-saving policies seek a balance between stabilizing economic growth and protecting the environment, actual energy-saving effects are not satisfactory [2]. To achieve long-term and green economic growth, China has announced targets to peak carbon emissions by 2030 and achieve carbon neutrality by 2060. Hence, a correct understanding of the characteristics of energy intensity (i.e., the ratio of energy use per economic output) at different stages of economic development is necessary for countries like China to formulate energy-saving and emission-reduction policies in both the short and long term.

A brief literature review (See Section 2) shows that energy intensity evolves with economic development and is influenced by various factors such as technological progress, economic structure, and institutional arrangement. Previous studies have studied either the relations between energy intensity and economic growth, or the roles of influencing factors of energy intensity. There is a knowledge gap on the characteristics of energy intensity associated with influencing factors at different economic development stages. This study intends to address the knowledge gap by a threshold regression analysis based on panel data from 21 developed countries, since the experience of developed countries is likely to be followed by emerging and less-developed countries.

Therefore, this paper mainly aims to analyze whether the impact of economic growth on energy intensity could change dramatically if one of the key influencing factors evolves from one stage to another by using threshold regression models based on panel data from 21 developed countries. Such an analysis is not only beneficial for decision makers to examine the stages of green and low-carbon development, but also has value for selecting an effective path of low carbon development and designing policy to promote ecological civilization development in developing countries like China.

The rest of the article is arranged as follows. The next section briefly reviews the relevant literature. Section 3 describes theoretical hypotheses, panel threshold models constructed, and the necessary variables and data involved in the models. Section 4 reports and discusses the modeling results. The last section concludes the analysis and provides policy implications.

2. Literature Review

Energy intensity is generally defined as the ratio of total energy input to gross domestic product (GDP) of an economy [3]. It is often used to compare the dependence on energy of economic development in different regions. Higher energy intensity indicates a higher cost of energy conversion into GDP, and lower energy intensity indicates a lower cost of energy conversion into GDP [4]. The energy intensity of most developed countries is declining with economic growth, while that of developing countries is still increasing [5,6]. This is mainly due to the growth rate of energy consumption in developed countries being slower than that of GDP [7,8]. This also means that every 1% increase in economic growth in developing countries requires an increase of more than 1% in energy use, while in developed economies less energy input is needed [9]. Due to the fluctuating trend of energy intensity in different countries, it is difficult to explain the internal principle and economic connotation of a single effect. For this reason, a variety of methods have been used in the literature to address the measurement of energy intensity. Broadly the methods can be divided into two categories. One category includes different decomposition methods, such as the structural decomposition method and exponential decomposition method, to intuitively decompose the change in energy intensity into driving factors, such as the changes in energy intensity at the sectoral level and the changes in sectoral output. The other category includes different regression models where energy intensity is taken as a dependent variable to examine the roles of important influencing factors.

Many studies have analyzed the influencing factors of energy intensity from different perspectives. In these studies, three types of influencing factors of energy intensity are identified as key driving forces, among others. The first type of factor is technological progress and efficiency improvement. Lin and Du [10] believe that technological progress is the main driving force of the decline in energy intensity. An improving technology level will directly improve the marginal productivity of energy, indirectly improve the efficiency of energy allocation, and then improve the efficiency of energy use, which plays a key role in the reduction in energy intensity [3,11,12]. The improvement of energy use efficiency is one of the main factors of energy intensity decline [13,14]. The second type of factor is changes in economic structure. Structural adjustment is one of the main means to reduce energy intensity [15]. The economic structure can be indicated by industrial, transportation, property rights, production factor, and energy consumption structures [16–20]. The third type of factor is institutional. Foreign institutional factors are mainly foreign direct investment (FDI) and import–export trade [21–23]. Domestic institutional factors, including urbanization, industrialization, agricultural modernization, informatization, environmental regulation, and market distortions [24,25], can affect the energy intensity of all countries. Besides these three types, there are other factors that affect energy intensity such as energy prices [26], total factor productivity [27], the consumer price index, and fiscal and taxation policies [28].

The driving factors of energy intensity changes mentioned above are closely related to economic development. Hence, some researchers directly study the relationship between energy intensity and the level of economic development. Suri and Chapman [29] found that higher income levels tend to correspond to lower energy intensity. Galli [30] showed that energy intensity would decline nonlinearly with an increase in per capita GDP in Asian countries in the long-term. Metcalf [31] also showed that energy intensity was falling as per capita income levels rise in the United States. Various studies have shown that energy intensity will rise in the early stage of economic development and decline in the middle and late stages [32–35]. In the literature, economic development is typically represented by the GDP level, not influencing factors considered in the present study.

3. Theoretical Hypothesis, Model Specification, Variable Selection, and Data Description

3.1. Theoretical Hypothesis

At different stages of economic development, the relationship between economic growth and energy intensity may switch from linear to nonlinear [36]. That is, when the economic development level is in low-income and high-income stages, the relationship between economic growth and energy intensity is shown as a linear relationship; in the middle-income stage, the relationship between economic growth and energy intensity is shown as a nonlinear relationship. In addition, the threshold of income level is used as a boundary to smoothly transition between the old and new mechanisms [37]. We argue that the nonlinear relations between economic growth and energy intensity are likely due to several key factors that drive the economic development. Hence, we propose the following contradictory theoretical hypotheses to be examined in this study:

Hypothesis 1 (H1)**.** *The relations between energy intensity and economic growth are irrelevant to the key factors of economic development including energy consumption structure, the level of urbanization, industrial structure, and technical level.*

Hypothesis 2 (H2)**.** *The relations between energy intensity and economic growth follow different patterns at various stages of key variables including energy consumption structure, the level of urbanization, industrial structure, and technical level.*

3.2. Model Specification

To empirically test which hypothesis is plausible, this study adopts threshold regression models, where a threshold effect refers to a phenomenon that occurs when an economic parameter reaches a critical value—another economic parameter suddenly turns to other forms of development. The critical value of the former parameter is called the threshold value. Hansen [38] proposed the first threshold regression model, using threshold variables to determine the structural change points and deal with the structural change of nonlinear problems more objectively and accurately. The advantage of a threshold regression model is that the model does not need to set a specific nonlinear functional form in advance, and the threshold values and their numbers are completely determined by the sample data. It can not only directly estimate the nonlinear relationship between the explanatory variable and the explained variable, but also test the significance of the "threshold" feature and its corresponding threshold value, which overcomes the shortcomings of traditional methods.

Based on the literature review in Section 2, three types of factors can affect energy intensity: technological progress, economic structure, and institutional arrangement. Following the indicators used in previous studies and considering the data availability, we consider four influencing factors indicating energy consumption structure, urbanization rate, industrial structure, and technological level, respectively. Hence, this paper constructs single, double, and triple threshold regression models for empirical testing. To save space, below we present only the illustrative specifications of single and double threshold regression models:

$$\begin{aligned}\ln ei_{it} &= \ln\alpha + \beta_1 \ln es_{it} + \beta_2 \ln ur_{it} + \beta_3 \ln ind_{it} + \beta_4 \ln tech_{it} + \lambda_1 \ln gdp_{it} I(q_{it} \le \gamma) \\ &+ \lambda_2 \ln gdp_{it} I(q_{it} > \gamma) + \varepsilon_{it}\end{aligned} \tag{1}$$

$$\begin{aligned}\ln ei_{it} &= \ln\alpha + \beta_1 \ln es_{it} + \beta_2 \ln ur_{it} + \beta_3 \ln ind_{it} + \beta_4 \ln tech_{it} + \lambda_1 \ln gdp_{it} I(q_{it} \le \gamma_1) \\ &+ \lambda_2 \ln gdp_{it} I(\gamma_1 < q_{it} \le \gamma_2) + \lambda_3 \ln gdp_{it} I(q_{it} > \gamma_2) + \varepsilon_{it}\end{aligned} \tag{2}$$

Equation (1) is a single threshold regression model, and equation (2) is a double threshold regression model. In the equations, $i$represents a country; $t$represents a time (e.g., a year); $\ln ei_{\mathrm{it}}$represents the energy intensity of country i at time t; q_{it} is the threshold variable, representing the variable that may display the threshold effect; $I(*)$ is the indicator function, with a value of 1 if the condition in brackets is met, and 0 if the condition is not met; $\ln gdp_{\mathrm{it}}$ is GDP per capita, the core explanatory variable whose effect on energy intensity depends on the threshold variable; $\ln es_{\mathrm{it}}$, $\ln ur_{\mathrm{it}}$, $\ln ind_{\mathrm{it}}$, and $\ln tech_{\mathrm{it}}$ are the candidate threshold variables that have significant impacts on energy intensity, representing energy consumption structure, urbanization rate, industrial structure and technological level, respectively; α, β, and λ are coefficients to be estimated; γ is a critical threshold value; and ε_{it} is a random disturbance term.

3.3. Variable Selection

The dependent variable is energy intensity, indicating the dependence of a country's economic and social development on energy consumption. Generally, the lower the energy intensity (less energy use per unit GDP), the lower the dependence of economic development on energy. The energy intensity in this study is calculated as primary energy use per unit GDP for a country, where GDP is measured at 2011 purchasing power parity (PPP) to eliminate the impact of prices.

The core explanatory variable is per capita GDP, a comprehensive indicator representing economic development stage of an economy. It has been argued that the higher the economic growth rate, the faster the energy intensity decreases [39]. Similarly, per capita GDP is also calculated at 2011 PPP to make it comparable over time.

Based on the literature reviews in Section 2 and data availability, we introduce each of the four control variables below as the threshold variable in a model specification to explore how the characteristics of economic and social development represented by the control variable might influence the relations between energy intensity and economic growth.

One control variable to indicate the energy consumption structure is the proportion of renewable energy consumption in total energy consumption. Renewable energy consumption here refers to the consumption of hydropower, wind power, nuclear power, and other renewable energy. The higher the proportion of renewable energy, the cleaner the energy consumption structure in terms of carbon emissions per unit energy consumption.

Another control variable is required to indicate the level of urbanization. There are two indicators to measure the level of urbanization in a region, i.e., the proportion of non-agricultural population in total population, and the proportion of urban population in total population. Although both indicators have been used in the literature to measure the level of urbanization, it does not lead to much contradiction in the context of China [40].

Considering data availability, the proportion of urban population in total population is adopted in this study.

The third control variable is used to represent the industrial structure. Compared with secondary industry, tertiary industry is generally regarded as a "cleaner" industry with relatively lower energy consumption and ecological cost. Therefore, we measure the industrial structure by the proportion of the output of tertiary industry in total output.

The fourth control variable is related to the technical level. R&D investment is the basis for the realization of technological innovation, which in future will promote the development of related technologies through the spillover effect. Hence, a continuous increase in R&D investment would potentially promote energy technological innovation to reduce energy intensity. We use the proportion of R&D expenditure in GDP to indicate the level of technology in a country.

3.4. Descriptive Statistics and Data Sources

To provide potential options of future sustainable development for emerging and less-developed countries, this paper chooses panel data of 21 developed countries from 1996 to 2015 as the research sample. The data are taken from the World Bank database (https://data.worldbank.org, accessed on 21 June 2021). In the database, the energy intensity data are available until 2015. Some developed countries are excluded due to the lack of data for certain year and necessary variables. For the other countries with complete data series, we consider three aspects, as follows: First, a country has the potential capacity to reduce energy intensity while keeping positive economic growth. Second, a country is classified as one of the high- and middle-income countries, has completed industrialization, and is a potential leader in energy savings. Third, scientific and technological means are extensively adopted in energy utilization. Hence, the following countries are included in our sample: Austria, Belgium, Czech Republic, Germany, Spain, Finland, France, United Kingdom, Hungary, Ireland, Israel, Italy, Japan, Korea, Mexico, Netherlands, Poland, Portugal, Slovakia, Slovenia, and Turkey.

To ensure the robustness of the estimated results and reduce the possible heteroscedasticity problems in the data, the natural logarithms of all the variables were used as the input data in the model. Table 1 shows the descriptive statistics of the relevant variables of the 21 developed countries from 1996 to 2015.

Table 1. Descriptive statistics of the main variables in terms of natural logarithms.

Variable	Explanation	Obs.	Mean	Std. Dev.	Min	Max
$\ln ei$	Energy intensity	420	1.5661	0.2859	0.6669	2.3290
$\ln gdp$	GDP per capita	420	10.2711	0.3397	9.3906	11.0156
$\ln es$	Proportion of renewable energy consumption	420	2.0736	1.2139	−2.1029	3.9037
$\ln ur$	Proportion of urban population in total	420	4.2744	0.1711	3.9249	4.5837
$\ln ind$	Proportion of the output of the tertiary industry in total	420	4.0998	0.0970	3.8817	4.2831
$\ln tech$	Proportion of R&D expenditure in GDP	420	0.3723	0.6345	−1.3836	1.4880

4. Empirical Test and Result Analysis

4.1. Benchmark Regression Analysis

Table 2 reports estimation results of five model specifications in the benchmark regression analysis (Stata 13 software, https://www.stata.com, accessed on 21 June 2021, is adopted for estimating all models in this study). The ordinary least squares (OLS) model in Column (1) considers only the core explanatory variable of per capita GDP. The estimated coefficient for the linear term of per capita GDP is positive and that for the squared term is negative, and both have high significance, indicating that energy intensity tends to increase more slowly or decline faster along with economic growth. Roughly speaking, this confirms that there exists a "Kuznets Curve," like the environmental pollution caused by energy consumption [41,42].

Table 2. Benchmark regression analysis.

Variable	(1) OLS	(2) OLS	(3) FE	(4) RE	(5) SYS-GMM
$\ln gdp$	7.4658 *** (2.2437)	−0.3395 *** (0.0478)	−0.7383 *** (0.0312)	−0.7362 *** (0.0319)	
$\ln gdp^2$	−0.3804 *** (0.1104)				
$L.\ln gdp$					−0.3270 *** (0.0602)
$\ln es$		0.0423 *** (0.0090)	−0.0463 *** (0.0110)	−0.0378 *** (0.0109)	0.0453 *** (0.0118)
$\ln ur$		0.3969 *** (0.0753)	−0.1250 (0.1319)	0.0063 (0.1256)	0.3984 *** (0.0688)
		−1.5638 *** (0.1449)	−0.9196 *** (0.1194)	−1.0115 *** (0.1202)	−1.5312 *** (0.1396)
$\ln tech$		0.1921 *** (0.0253)	0.0697 ** (0.0229)	0.0824 *** (0.0231)	0.1815 *** (0.0250)
_cons	−34.9383	9.6089	13.5252	13.2965	9.3338
R^2	0.1236	0.4830	0.7670	0.7658	0.4742
chi2 (6)			32.76		

Note: ***, ** respectively indicate significance at the level of 1%, and 5%, and the values in parentheses indicate standard errors.

The model specification of Column (2) replaces the squared per capita GDP by the four control variables, and the estimated results show that economic growth (GDP growth) has a significant impact on energy intensity after adding the control variables, and that the coefficients of all the explanatory variables are significant at the level of 1%. As a result, the estimated coefficient for the linear term of per capita GDP becomes negative, indicating that higher economic growth corresponds to lower energy intensity, which is consistent with the general perception. Notice that if the squared term of GDP is also included in this specification, then its coefficient becomes insignificant, indicating the non-linear effect of the GDP has been captured by the four control variables.

Columns (3) and (4) presents the results of fixed effect (FE) and random effect (RE) specifications. The Hausman test [43] is used to determine which model is more effective, and the test result suggests that the fixed effect model is better than the random effect model. We also use the F-value to test the applicability of the fixed-effect model, and the null hypothesis is rejected at the significance level of 1%, suggesting that the fixed-effect model is more effective.

Although the fixed-effect model can eliminate the influence of unobservable factors that do not change over time to a certain extent, the influence of other unobservable factors will inevitably bring endogenous problems, which leads to errors in OLS and fixed-effect estimation. The model in Column (5) is a dynamic panel regression model, introducing the lagged term of per capita GDP to reduce the potential endogeneity of the model. The system generalized moment estimation (SYS-GMM) was used to test the relations between economic growth and energy intensity. The estimated coefficient of the lagged per capita GDP is very close to that of the current per capita GDP in the OLS model Column (2), confirming that the endogeneity is not a problem.

We also conducted unit root and multicollinearity test to reduce the phenomenon of pseudo-regression due to non-stationary variables. Since our data are short panel data, we adopted the panel unit root HT test [44]. According to the test, we found non-stationary variables and the cointegration test is necessary. The Pedroni test [45] results shown in Table 3 indicate a co-integration relationship between these variables. Hence, the data are stable.

Table 3. Panel Cointegration Test.

	Panel Means	**Time Trend**	**None**
Modified Phillips–Perron t	6.4448 ***	5.2034 ***	4.6425 ***
Phillips–Perron t	−11.7688 ***	−10.3956 ***	−6.5908 ***
Augmented Dickey–Fuller t	−20.1865 ***	−18.2295 ***	−5.6362 ***

Note: *** indicates that the null hypothesis with co-integration relationship is rejected at a significance level of 1%.

In addition, the multicollinearity of each variable was tested, and the variance inflation factor (VIF) was used to judge whether there was multicollinearity between the variables. The larger the VIF value, the more obvious the collinearity problem. Generally, multicollinearity is not seen a problem if a VIF value is less than 10. The multicollinearity test results in Table 4 show that the VIFs of all explanatory variables are less than 3, where the largest is 2.59, and the average is 1.97. Therefore, multicollinearity is not an issue between the variables.

Table 4. Multicollinearity test.

Variable	**VIF**	**1/VIF**
$\ln gdp$	2.59	0.3859
$\ln tech$	2.54	0.3942
$\ln ind$	1.94	0.5160
$\ln ur$	1.63	0.6143
$\ln es$	1.18	0.8488
Mean VIF	1.97	

4.2. Threshold Test

4.2.1. Identification of the Existence of Threshold Effects

Based on Hansen's threshold model and 300 repeated samplings, threshold effect tests were performed by using the Stata codes developed by Lian and Cheng [46], and the results were shown in Table 5. For the energy consumption structure, the single and double thresholds are significant at the 10% level and the triple threshold is not significant. For the urbanization level, the single and double threshold effects are significant at the 5% level and the triple threshold effect at the 1% level. For the industrial structure, all the three threshold effects are significant at either the 1% or 5% level. For the technical level, only the single and double threshold effects are significant at the 5% and 1% levels, respectively. These results indicate that each of the four threshold variables has certain threshold effects on the relations between economic growth and energy intensity.

Table 5. Test results of threshold effect.

					Critical Value		
Threshold variable	Threshold number	*F*value	*p* value	BS times	1%	5%	10%
	Single threshold	22.003 *	0.100	300	44.545	30.407	21.746
$\ln es$	Double threshold	22.722 *	0.083	300	42.978	29.032	20.797
	Triple threshold	14.125	0.110	300	32.200	23.352	14.503
	Single threshold	63.164 **	0.040	300	97.617	58.485	46.202
$\ln ur$	Double threshold	52.120 **	0.023	300	58.428	41.144	29.988
	Triple threshold	32.867 ***	0.033	300	44.079	26.708	20.649
	Single threshold	75.439 ***	0.007	300	72.999	48.192	38.057
$\ln ind$	Double threshold	16.792 **	0.040	300	23.895	16.433	9.348
	Triple threshold	9.089 **	0.040	300	15.134	8.075	6.283
	Single threshold	25.055 **	0.040	300	32.805	22.181	16.301
$\ln tech$	Double threshold	34.758 ***	0.003	300	30.915	18.742	15.404
	Triple threshold	8.186	0.130	300	23.111	13.463	9.122

Note: ***, **, * respectively indicate significant at the level of 1%, 5%, and 10%.

4.2.2. Estimation of Critical Values of Threshold Variables

After the threshold effects are identified by the test in the above subsection, the critical values of the threshold variables need to be estimated and tested for the cases of the identified threshold effects. Table 6 lists the estimated threshold values for the energy consumption structure, urbanization, industrial structure, and technological level and their 95% confidence intervals. It can be concluded that the threshold values in all the models for the identified threshold effects are statistically significant since the estimated values fall within the 95% confidence intervals.

Table 6. Threshold estimates and confidence intervals.

Variable	γ_1		γ_2		γ_3	
	Estimated Value	**95% Confidence Interval**	**Estimated Value**	**95% Confidence Interval**	**Estimated Value**	**95% Confidence Interval**
$\ln es$	2.586	[2.581,2.608]	2.911	[1.647,2.924]		
$\ln ur$	4.015	[4.009,4.018]	4.260	[4.260,4.260]	4.509	[4.509,4.509]
$\ln ind$	3.969	[3.967,4.212]	4.173	[3.967,4.182]	4.235	[4.234,4.235]
$\ln tech$	0.162	[0.152,0.162]	0.497	[0.487,0.499]		

4.2.3. Estimation Results of Threshold Regression Models

The estimated results of all the models for the identified threshold effects are reported in Table 7. They show that the estimated coefficient of per capital GDP always has negative values in all the threshold regression models, which are significant at the 1% level. This indicates that energy intensity tends to decline with faster economic growth for these developed countries, although the declining speed of energy intensity varies depending on which model is used. According to the results, a 1% increase in GDP per capita can lead to a 0.62–0.78% reduction in energy intensity, implying economic growth can significantly reduce the energy intensity, although the effect is not one-to-one, probably due to a rebound effect caused by relatively lower energy prices [47].

Table 7. Threshold regression estimations of the relations between per capita GDP and energy intensity.

Variable	**Threshold Regression Model**			
ln*ei*	**ln*es***	**ln*ur***	**ln*ind***	**ln*tech***
$\ln gdp(q_{it} \leq \gamma_1)$	−0.7295 *** (0.0297)	−0.6445 *** (0.0302)	−0.7770 *** (0.0298)	−0.7834 *** (0.0300)
$\ln gdp(\gamma_1 < q_{it} \leq \gamma_2)$	−0.7312 *** (0.0298)	−0.6516 *** (0.0300)	−0.7640 *** (0.0300)	−0.7664 *** (0.0297)
$\ln gdp(\gamma_2 < q_{it} \leq \gamma_3)$	−0.7226 *** (0.0298)	−0.6354 *** (0.0309)	−0.7599 *** (0.0297)	−0.7745 *** (0.0300)
$\ln gdp(q_{it} > \gamma_3)$		−0.6176 *** (0.0304)	−0.7642 *** (0.0300)	
$\ln es$	−0.0623 *** (0.0112)	−0.1051 *** (0.0113)	−0.0585 *** (0.0105)	−0.0284 *** (0.0108)
$\ln ur$	−0.0261 (0.1273)	−0.3903 ** (0.1272)	0.2858 ** (0.1259)	−0.1355 (0.1240)
$\ln ind$	−0.9232 *** (0.1137)	−0.6254 *** (0.1059)	−0.6131 *** (0.1319)	−0.8244 *** (0.1128)
$\ln tech$	0.0733 *** (0.0218)	0.0118 (0.0203)	0.0336 (0.0209)	0.1453 *** (0.0236)
cons	13.0537	12.4764	10.8002	13.5019
R^2	0.7900	0.8329	0.8141	0.7970

Note: ***, ** respectively indicate significance at the level of 1%, and 5%, and the values in parentheses indicate standard errors.

For the other control variables themselves, the energy consumption structure, represented by the proportion of renewable energy consumption in total, has a significantly negative impact on energy intensity. This is understandable since renewables are relatively more costly for producers (or expensive for households) and discourage energy consumption. The industrial structure, represented by the proportion of the output of tertiary industry, tends to have negative relations with the energy intensity, which is reasonable as the tertiary industry has relatively low energy intensity. Surprisingly, the technical level, represented by the proportion of R&D expenditure in GDP, always has positive values of the estimated coefficients, indicating that more R&D expenditure tends to accompany higher energy intensity in these countries. The level of urbanization, represented by the proportion of urban population, has negative estimated coefficients except in the models considering the threshold effect of the industrial structure. The negative values are understandable as one urban person creates more economic value than one rural person on average. The positive value is likely caused by the correlations between the urban population and tertiary industry, as the increased urban population in a later stage tends to work in the tertiary industry. Below we focus on the threshold effects of each threshold variable.

First, the threshold effects of the energy consumption structure: the energy consumption structure shows single and double threshold characteristics in the relationship between economic development and energy intensity. When the energy consumption structure is lower than the threshold value of 2.586, the estimated coefficient of per capita GDP is -0.7295. When the energy consumption structure is between 2.586 and 2.911, the coefficient of per capita GDP becomes -0.7312. When the energy consumption structure is higher than the threshold value of 2.911, the coefficient of per capita GDP is -0.7226. This indicates that economic growth tends to promote the decline of energy intensity the most when the proportion of renewable consumption is at an intermediate level. The results imply that more renewable energy consumption may slow down the promotion effect of economic growth on the decline of energy intensity after a certain stage, although more renewable consumption itself is good for reducing energy intensity. This is consistent with Lin and Li [48], who argue that renewable energy is an immature form of energy utilization, which requires a large amount of R&D investment to promote the economic cost reduction under technological progress, further affecting the market competitiveness of renewable energy against traditional energy.

Second, the threshold effects of the level of urbanization: the level of urbanization presents triple threshold effects in the relationship between economic development and energy intensity. When the level of urbanization is lower than the threshold value of 4.015, the impact coefficient of the per capita GDP on energy intensity is 0.6445. When the level of urbanization is between 4.015 and 4.260, the impact coefficient of the per capita GDP on energy intensity is 0.6516. When the level of urbanization is between 4.260 and 4.509, the impact coefficient of the per capita GDP on energy intensity is 0.6354. When the level of urbanization is higher than the threshold value of 4.509, the impact coefficient of the per capita GDP on energy intensity is 0.6176. These results imply that more urban population can enhance the decline of energy intensity associated with economic growth at the early stage and the enhancing effect disappears and even slows down the decline of energy intensity after the urban population achieves a certain level. This is comparable to Shi [49], who concludes a significant double threshold effect between urbanization and energy intensity.

Third, the threshold effects of the industrial structure: the industrial structure presents triple threshold characteristics in the relationship between economic development and energy intensity. When the industrial structure is lower than the threshold value of 3.969, the impact coefficient of per capita GDP on energy intensity is 0.7770. When the industrial structure is between 3.969 and 4.173, the regression coefficient of per capita GDP to energy intensity is 0.7640. When the industrial structure is between 4.173 and 4.235, the regression coefficient of per capita GDP to energy intensity is 0.7599, when the industrial structure is higher than the threshold value of 4.235, the regression coefficient of per capita GDP to energy intensity is 0.7642. The results imply that the development of tertiary industry can weaken the decline of energy intensity associated with economic growth and then enhance slightly after a certain advanced stage. The results complement previous studies [50] stating that the optimization and upgrading of industrial structure is an important measure to reduce energy intensity during economic growth.

Lastly, the threshold effects of the technical level: the technological level presents a single and double threshold in the relationship between economic development and energy intensity. When the technology level is lower than the threshold value of 0.162, the influence coefficient of the per capita GDP on energy intensity is 0.7834. When the technology level is between 0.162 and 0.497, the regression coefficient of the per capita GDP to energy intensity is 0.7664. When the technology level is higher than the threshold value of 0.497, the regression coefficient of the per capita GDP to energy intensity is 0.7745. These results imply that the technical level may weaken at the early stage and then enhance after a certain stage the decline of energy intensity associated with economic growth. This is consistent with findings in previous studies. It has been found that R&D investment can contribute to an increase in energy intensity, although it contributes to the reduction of energy intensity significantly at some stages [51]. A study has also concluded that a threshold effect of R&D investment on carbon emissions exists [52]. When R&D investment is less than a certain level, it will increase carbon emissions, and so to a certain extent it does not play a beneficial role in reducing emissions.

5. Conclusions

Under the background of global green development and carbon neutral strategy, the main purpose of this paper is to deepen the understanding of the relationship between economic growth and energy intensity, which is affected by key factors of economic development. This paper uses panel data from 21 developed countries from 1996 to 2015 to empirically test and analyze the threshold impact of economic growth on energy intensity related to key influencing factors including energy mix, urbanization, industrial structure, and technological progress. At different stages of economic development characterized by these key influencing factors, a linear model may not accurately describe the complex nonlinear relationships between economic growth and energy intensity. Hence, panel threshold regression models are constructed in this paper to explore the nonlinear effect of economic growth on energy intensity at different stages of economic development. These models can not only directly estimate the nonlinear relationship between the explanatory and the explained variable, but also test the significance of the "threshold" feature and its corresponding threshold value, which overcomes the shortcomings of linear regression models.

We found that a 1% increase in GDP per capita can lead to a 0.62–0.78% reduction in energy intensity, implying economic growth can significantly reduce energy intensity, although the effect is not one-to-one. The extent of the reduction in energy intensity varies depending on the economic development stages represented by key influencing factors. Specifically, the reduction in energy intensity due to economic growth can be enhanced with relatively more renewable energy consumption and more urban population until a threshold point, where the enhancement disappears. On the other hand, the extent of the energy intensity reduction due to economic growth can be weakened with relatively more tertiary industry activities and more research and development (R&D) expenditure in an economy, until a threshold point where the weakening cannot continue. However, compared to the stages represented by the low ends of renewable consumption, urban population, tertiary industrial activities, and technological progress, the later stages represented by the high ends of these key factors imply a weakened effect of economic growth on the decline of energy intensity.

The findings of this paper provide certain suggestions for the formulation of energy policies. This paper confirms the strong correlation between the decline in energy intensity and the rate of economic growth, implying a policy to promote economic growth is a good choice to reduce energy intensity. In other words, reducing energy intensity does not mean sacrificing economic growth. It is possible for countries to promote economic development while reducing energy intensity. However, the threshold effects related to the key influencing factors of economic development shown in this paper suggest policy makers, particularly from developing countries, should adjust their expectations on the declining energy intensity associated with economic growth, and particularly lower their expectations at the well-developed stages.

Nevertheless, this paper also has certain shortcomings. For various reasons, such as data availability, only 21 developed countries are considered in this study. In future research, it would be of benefit to include more developed and even developing countries, data from a longer time period, more key influencing factors, and to improve representativeness.

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