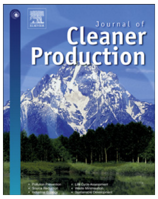
Journal of Cleaner Production 234 (2019) 1013–1022

Contents lists available at ScienceDirect

Journal of Cleaner Production

journal homepage: www.elsevier.com/locate/jclepro



Investigating environmental Kuznets curve from an energy intensity perspective: Empirical evidence from China

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ARTICLE INFO

Article history:
Received 4 December 2018
Received in revised form
11 June 2019
Accepted 12 June 2019
Available online 13 June 2019

Handling editor: Bin Chen

Keywords:
Energy intensity
Environmental kuznets curve
Pollution emissions
Panel smooth transition regression

ABSTRACT

This study pioneers investigating the environmental Kuznets curve (EKC) hypothesis and its possible regional differential characteristics in China. Based on 2003–2017 years of provincial panel data, this research employs panel smooth transition auto regression (PSTR) model to analyze the impact of income levels on environmental pollution and identify the EKC threshold of energy intensity. Then, 30 Chinese provinces were categorized by energy intensity to examine the inter-provincial and interregional differences in the EKC threshold of energy intensity, rather than the traditional threshold of income. The results indicate that China's pollution emissions and energy intensities show a stepwise decreasing pattern from the western region to the eastern region. In addition, the impact of income levels on pollution emissions is non-linear, and the critical value of energy intensity is 0.9168 between the high- and low regimes. An inverted U-shaped environmental Kuznets curve is accepted for energy intensity, with 0.7670 as its threshold value. When the energy intensity is higher (lower) than the threshold value, the income elasticity of pollution emission is positive (negative). The more developed provinces and municipalities mainly in the eastern region are proved to exceed the threshold than the provinces in the central and western regions within the sample period. Given these findings, this study further divides China's provinces into eco-friendly, low-pollution, and high-pollution provinces, and accordingly, the most important policy recommendations were discussed for policy-makers and researchers. This research can provide a new insight to investigate countries with unbalanced development levels within and a reference for environmental governance policies in sub-regions.

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1. Introduction

Over the last few decades, since China join WTO, it has experienced substantial growth in its social and economic development and human welfare, which, in turn, has increased its demand for energy, especially the fossil fuels. Regardless of the large efforts made by China to decrease its pollution and increase the role of renewable energy, energy efficiency, and energy conservation, fossil fuels still represent the dominant source of energy use, accounting for almost 70% of the total domestic energy consumption (*World Development Indicators, 2018*). Therefore, the world has witnessed a large environmental degradation problem in China, which is also one of the major concerns that countries around the globe, including both developed and developing ones, are currently confronted with. This dilemma has made many researchers interested in exploring the relationship between macroeconomic variables (GDP in particular), pollution emission, and energy consumption among different countries using different econometric methodologies. Among the wide range of the literature that has investigated the relationship, one of the most discussed issues is the environmental Kuznets curve (EKC) hypothesis, analogous to the pattern Kuznets (1955) found between income inequality and economic development. According to this EKC-hypothesis, environmental pressure tends to rise faster than income growth in the early stages of economic development, then slows down, reaches a turning point and declines with further income growth (Rothman and De Bruyn, 1998). This means that since the peak of the curve, the economy is slowing down the use of materials and energy input in the production process (Grossman and Krueger, 1991), implying income growth will become a cure for environmental problems. It

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https://doi.org/10.1016/j.jclepro.2019.06.121
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also has been interpreted as a possible de-linking of economic growth and patterns of certain pollutants for developed economies (Simonis, 1989; IBRD, 1992).

However, it is argued that there is no guarantee that economic growth will lead to an improved environment – in fact, the opposite is often the case. At the least, it requires targeted policy and attitudes to make sure that economic growth is compatible with an improving environment. It should be noted that the massive use of fossil fuels in China during its process of modern industrial development is the primary cause for environmental pollution and that China and countries alike with high energy intensity are likely to have more severe pollution problems. (Fig. 1). The mechanism behind may be as follows: before exceeding the threshold, the industrial structure is dominated by pollution-intensive industries, the level of production technology being relatively low, with high energy intensity, and income growth leads to increased pollution. After exceeding the threshold, as income levels rise, the optimization of industrial structure and advancements in production technology lead to reduced energy intensity, thereby lowering pollution levels. Its essence is the transition from an energy-intensive model of economic development with high energy consumption and pollution levels to an eco-friendly one.

Environmental pollution in one country or region will not naturally improve with a rise in income levels, but requires improvements in industrial structure and technological levels (Greyson, 2007; Van den Bergh and Jeroen, 2011; Kang et al., 2016; Ahmad et al., 2017a,b; Wang et al., 2018), which will lead to the decrease of energy intensity. Thus, successful governance and regulations of environmental pollution can be achieved by means of reducing energy intensity. Therefore, it is greatly important for researchers and policy makers to know the features of the EKC from the perspective of energy intensity in different countries and their various periods.

The Environmental Kuznets Curve (EKC) hypothesis, proposed by Grossman and Krueger (1991, 1996), postulates an inverted-U-shaped relationship between different pollutants and per capita income, i.e., environmental pressure increases up to a certain level as income goes up; after that, it decreases. Since this hypothesis was proposed, it has been fiercely discussed (Dinda, 2004, 2005). In the earlier stage, the concern was mainly focused on its possibility of existing and its shape features, if any. For example, Panayotou (1993) used GDP per capita measuring income levels to measure environmental pollution, particularly sulfur dioxide (SO2) and nitrous oxide (NOx) emissions, and damages to the ecological environment. He found an inverted U-shaped relationship between environmental pollutants and income levels. This proved hypothesis was then supported by many studies such as Cropper and Griffiths (1994), Stern et al. (1996), Carson et al. (1997), Wang and Wheeler (2000), Tsurumi and Managi (2010), Onafowora and Owoye (2014), Benavides et al. (2017), and Sarkodie and Strezov (2018) etc. However, some other researchers stood in opposition to the conclusions, stating that the EKC takes different shapes other than the inverted U or does not exist at all (Holtz-Eakin and Selden, 1995; Bertinelli and Strobl, 2005; Wagner, 2008; Auffhammer and Carson, 2008; Chuai et al., 2012). Webber and Allen (2010) showed that the turning point of the EKC corresponds to high per capita income, such that the EKC for a majority of the regions depicted a monotonic increase. In other words, the degree of environmental pollution continued to worsen with increasing income levels. Brajer et al. (2008) and Brajer et al. (2011) performed empirical analyses on data from China and found that the EKC was N or W shaped. Caviglia-Harris et al. (2009) conducted a similar study from the perspectives of an ecological footprint and environmental pressure and showed that the EKC does not exist and increased income levels did not improve the ecological environment. The conclusion of the non-existence of the EKC is also reached in some cases of the studies (Lin et al., 2016; Kang et al., 2016; Wang and Ye, 2017).

Because the conclusions reached by related studies are not consistent, researchers began to criticize the inconclusiveness of the EKC hypothesis, and tried to give interpretations from various selection of the models and indicators. Some studies on the EKC employed cross-section or panel data techniques to discuss the link between environmental degradation and economic growth (for example, Farhani et al., 2014; Apergis, 2016; Zoundi, 2017). However, they failed to offer further policy implications for a single country (Ang, 2008), because the pollution path was set as the same for individual countries in different developing stages (Lindmark, 2002; Friedl and Getzner, 2003; Arbulú et al., 2015; Dong et al., 2018). For instance, researchers concluded that pollution-income relationships from the cross-country studies (Grossman and Krueger, 1991; Shafik and Bandyopadhyay, 1992; Panayotou, 1993; Selden and Song, 1994; Fodha and Zaghdoud, 2010; Özokcu and Özdemir, 2017) fail to accurately predict the trends in air and

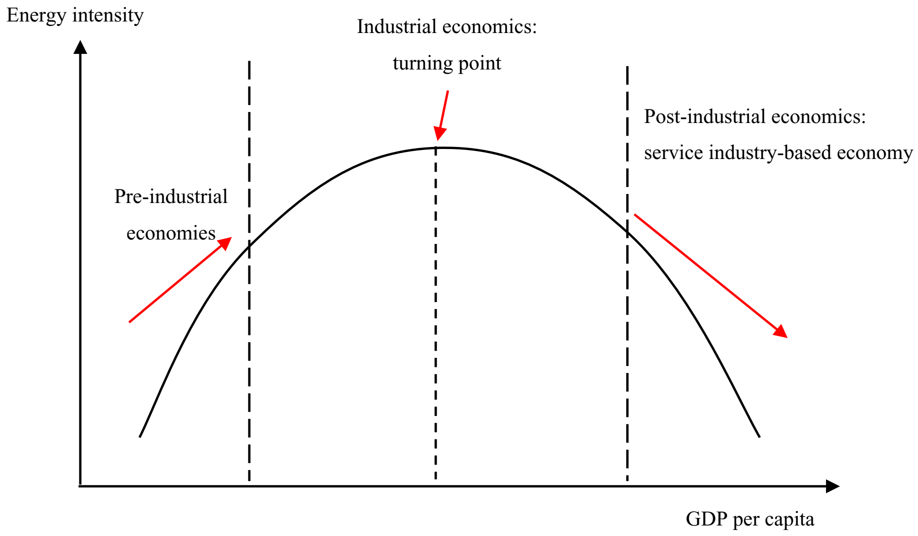

Fig. 1. Kuznets curve of energy intensity.

water pollution in Malaysia (Vincent, 1997), Latin America (Bhattarai and Hammig, 2001), Arctic countries (Baek, 2015). As Stern (2004) pointed, different empirical models and data indicators will inevitably lead to inconsistent results, and thus, the lack of a definite curvilinear relationship between environmental pollution and income levels. The studies of Saboori et al. (2012) and Bekhet and Othman (2017) also indicated that the lack of a common EKC for all countries showed the necessity to carry out studies on individual countries to ensure the institution of effective, sustainable, development policies.

Then some researchers switched to study the EKC hypothesis in individual countries using advanced time series econometric models, and many indicators of environmental degradation, in addition to CO2, are included in the related studies. The methods using time series techniques for a single country started from the studies of Dijkgraaf and Vollebergh (1998) for individual OECD countries; De Bruyn et al. (1998) for Netherlands, West Germany, UK and USA; Roca et al. (2001) for Spain; Day and Grafton (2003) for Canada and Friedl and Getzner (2003) for Austria. Then, the EKC hypothesis is extensively tested in individual countries, for example, Jalil and Mahmud (2009) in China, Bahmani and Gelan (2008) in US, He and Richard (2010) in Canada, Tutulmaz (2015) for Turkey, Al-Mulali et al. (2015) for Vietnam, Balaguer and Cantavella (2016) for Spain, Ahmad et al., 2017a,b in Croatia, Solarin et al. (2017) in India and China. In recent years, a large number of studies have been conducted on the EKC, mainly on exploring the effect of different pollutants. A majority of studies have examined the relationship between carbon dioxide (CO2) emissions and income levels (for example, Alam et al., 2016; Bilgili et al., 2016; Wang et al., 2017; Riti et al., 2017). In order to provide evidence in support of the EKC hypothesis, some studies attempted to find the potential determinants of CO2 emissions such as energy consumption by urbanization by Xu et al. (2018), industrial structure by Wang et al. (2019), technological progress by Ahmed et al. (2016), foreign trade by Jebli et al. (2016). However, the multivariate studies also produce conflicting results on the existence of EKC. In fact, inconclusive results with regard to the existence of EKC in studies on individual countries cannot be extrapolated as evidence of similar results for all countries.

Currently, some researchers begin to realize the importance of investigating the effect of other pollutants, SO2, NOx, PM10, etc. On environmental degradation. While CO2 is the most important gas that leads to greenhouse effect, PM10 and SO2 are the most harmful local air pollutants (Akbostancı et al., 2009). Then the EKC was tested by some studies for SO2 by Danaeifar (2014), NOx by Sinha and Bhatt (2017) and Ge et al. (2018), and PM10 by Dong et al. (2019), but reaching different conclusions. For example, the study of Wang et al. (2016) used a semi-parametric panel data analysis for China to support inverted U-shaped curve relationship between economic growth and sulfur dioxide emissions, but found little evidence supporting a similar inference for the urbanization and those emissions. Du et al. (2018), on the other hand, found that the relationship between the haze pollution and economic growth in China is not a typical inverted U-shaped.

It should be noted that individual countries in different economic development levels have various income levels, industrial structures, technological progress, and environmental regulation etc. Because of these factors, it is hard to get a common featured EKC among individual countries, especially when developed and developing countries are investigated together. Hence, it is more meaningful to analyze the countries or regions at the equivalent levels, say, developing countries in aspects above, or to study more detailed characteristics between the environment degradation and regional income levels.

China, as the biggest developing country, has experienced substantial growth and also witnessed a serious environmental degradation problem. This has attracted many researchers to explore the relationship between economic growth and the environmental pollution (Pal and Mitra, 2017; Xu, 2018, etc.) In addition to the literature above, the literature that focus on China mainly test the EKC hypothesis and examine the regional differences and governance of environmental pollution. Deng et al. (2014) applied a generalized additive model to test the EKC in China and found that it displayed a monotonic increase and not the traditional inverted U shape. Furthermore, the economic scale and technological advancements were key factors influencing carbon emissions. Zou et al. (2014) applied dynamic optimization to show that the EKC hypothesis could be established in China but China is yet to exceed its turning point. Li et al. (2016) applied dynamic panel estimations to study the EKC hypothesis with Chinese panel data, robust supporting the EKC hypothesis for all the three indicators of pollution. Kang et al. (2016) supported this hypothesis by spatial panel data evidence.

In addition, Chinese researchers have adopted different perspectives to analyze influencing factors and governance policies for environmental pollution. Niu et al. (2012) proposed that industrial structure adjustments and environmental regulations enhancements will facilitate improvements in environmental pollution. Xiao and Liu (2014) analyzed the causes of environmental pollution from the viewpoint of industrial structure adjustments and showed that the equalization of the industrial structure had a significant limiting effect on industrial SO2 emissions, but the optimization of the industrial structure had an inhibitory effect on per capita emissions in the eastern regions. Qi and Wang (2015) analyzed pollution emissions in China from the viewpoint of regional and income differences. Their study confirmed that emission intensity showed a trailing inverted U shape as income increased and accordingly, they proposed regional governance measures on the basis of income levels. Han et al. (2016) and Qi et al. (2016) explored the effects of environmental regulation and found that the impact of environmental regulations on pollution and economic growth was dependent on technological advancements, regulatory environment, and other factors. The studies have been further followed by Zhao and Luo (2017), Hao et al. (2018), and Chen et al. (2018), etc.

Through a systematic review of previous studies, we could have reached a convincing conclusion that a common environmental Kuznets curve was not accepted and more detailed regional or industrial differences should be considered when individual countries are investigated. Despite the series of related studies concerning China's environmental Kuznets curve and its affecting factors, the research on China's EKC still requires further explorations because of the following three reasons at least: first, sulfur dioxide (SO2), if not PM10, should be regarded as a more important indicator of local pollution rather than carbon dioxide CO2 emission when environmental degradation of individual developing countries or regions are investigated, while CO2 emissions is more globally important because it brings about the greenhouse effect. For China, owing to the coal-dominated energy mix, SO2 has been one of the principal gas pollutants. Second, energy intensity, as the indicator used to assess the efficiency of comprehensive energy utilization in a country or region, to the best of our knowledge, has been largely overlooked and not sufficiently used in the existing EKC related literature, whereas energy utilization is the main cause of environmental pollution. China's rapid and massive economic growth, industrialization, and urbanization have been accompanied by soaring use of energy and a remarkable increase of harmful pollutants over that period. In practice, controlling environmental degradation usually start from decreasing its energy intensity, as Wang et al. (2016) suggested that an increase in energy intensity significantly contributes to the sulfur emissions load. Third, most of the previous studies mainly discussed the possibility of the existence of EKC hypothesis between countries among in individual countries and gave corresponding causes analysis, lack of further detailed insights from different industrial or regional levels in a single country. While some of the previous research primarily used linear regression, time-series, co-integration analysis, panel data, and spatial techniques to have some effective studies, few of them consider the inter-provincial and interregional differences categorized by energy intensity to examine the EKC threshold of energy intensity.

In addition, models based on both time series data and panel data have mainly taken the form of baseline models that include quadratic or cubic terms of per capita GDP. However, the specification of such models involves a certain degree of human subjectivity. González et al. (2005) proposed the panel smooth transition regression (PSTR) model, which enables the smooth transition of regression coefficients in the model between different regression regimes. This method not only better captures the non-linear features of panel data but also avoids the subjectivity of human model specification. Therefore, the empirical analysis of using the PSTR model will make it more convincing to examine the non-linear relationship between pollution emissions and income levels in China and identify the EKC threshold of energy intensity.

The objective of the study is, therefore, to test empirically the environmental Kuznets curve of energy intensity in different regions of China as one representative of the developing countries. Based on 2003–2017 years of provincial panel data, this study first analyzes the impact of income levels on environmental pollution and identifies the EKC threshold of energy intensity. Then, it categorizes Chinese provinces by energy intensity to examine the inter-provincial and interregional differences in the EKC threshold. And based on the results, it further divides China's provinces into eco-friendly, low-pollution, and high-pollution provinces, and tries to give more proper policy implications under the background of unbalanced regional development in China.

Compared to the existing literature, this study contributes in two ways. First, it identifies China's EKC threshold from an energy intensity perspective rather than the traditional threshold of income level. Second, after categorizing Chinese provinces by energy intensity, this study examined the inter-provincial and interregional differences in the EKC threshold. Base on it, all the provinces into eco-friendly, low-pollution, and high-pollution provinces. In addition, we choose sulfur dioxide as the pollutant indicator and use the PSTR model to investigate China's EKC hypothesis and capture the possible regional differential characteristics in China. It aims to provide a new insight to investigate countries with unbalanced development levels within and reference for environmental governance policies in sub-regions.

2. Model and data

2.1. PSTR model and variable selection

The model form in classic studies on EKC mainly introduces the quadratic term of income in the regression of pollution emissions. However, in this study, the PSTR model can naturally capture the non-linear characteristics between the variables and does not require human specifications. Since we emphasize the impact of energy intensity on the root causes of pollution emissions, the energy intensity variable is introduced in our model. In addition, energy intensity is set as a transition variable in the PSTR model, which assumes that the effect of income on pollution emissions varies by changes in energy intensity. Furthermore, referencing Xiao and Liu (2014) and Qi and Wang (2015), we select the industrial structure and intensity of environmental regulations as control variables. The PSTR model form is as follows:

$$\begin{cases} Y_{it} = \alpha_i + \beta_1 PGDP_{it} + \beta_2 IS_{it} + \beta_3 ER_{it} + \\ \quad \sum_{k=1}^{K}\left(\beta_1^k PGDP_{it} + \beta_2^k IS_{it} + \beta_3^k ER_{it}\right)\Gamma^k(IE_{it};.) + \varepsilon_{it} \\ \Gamma^k\left(IE_{it};\gamma^k,\overline{IE}_h^k\right) = \left[1 + \exp\left(-\gamma^k \prod_{h=1}^{H_k}\left(IE_{it} - \overline{IE}_h^k\right)\right)\right]^{-1} \end{cases}, \tag{1}$$

where the explained variable $Y$is emission intensity, the core explanatory variable $PGDP$ is per capita GDP, the transition variable IE is energy intensity, the control variables $IS$and $ER$are industrial structure and intensity of environmental regulations, $\alpha_i$is a parameter that represents fixed individual effect, $\varepsilon_{it}$is the random disturbance term, t:1−T is the sample time span, Γ^k (k = 1−K) is the transition function in the logistic form, each transition function includes h (h = 1−H_k) location parameters, $\overline{IE}$is the location parameter, and γ^k is the smoothness parameter.

As for data processing, the explained variable (emission intensity) in this study is expressed as the ratio of industrial SO_2 emissions to real value added of industry (VAI). A key reason for choosing SO_2 is that the statistical data for SO_2 is fairly complete and its data quality is relatively high. Furthermore, China's energy structure is dominated by coal and SO_2 is a major pollutant from coal production, and thus, SO_2 constitutes a major component of air pollution. SO_2 is also a variable commonly used in the existing literature. Since the growth rate index for VAI has not been published, it is calculated by multiplying the proportion of nominal VAI over nominal GDP with real GDP. Real GDP is obtained through a GDP index adjustment using 2003 as the base year. The explanatory variable (real per capita GDP) is derived on the basis of a per capita GDP index adjustment using 2003 as the base year. The transition variable (energy intensity) is expressed as the ratio of total energy consumption to regional real GDP. The industrial structure is expressed as the proportion of output value from secondary industries and intensity of environmental regulations is the ratio of completed investments in waste gas control to total industrial SO_2 emissions. To calculate the income elasticity of pollution emissions, we adopted the natural logarithms of pollution emissions and real per capita GDP. All raw data are from *the China Statistical Yearbook, China Environment Statistical Yearbook, China Energy Statistical Yearbook, and the China Economic Information Network (CEInet) Statistics Database*. The sample time span was 2003–2014 and included a total of 30 provinces, autonomous regions, and municipalities in China. Since data prior to 2003 and from Tibet are missing, these are excluded from our sample.

Given the specifications above, the income elasticity of pollution emissions is as follows:

$$\delta_{it} = \frac{\partial Y_{it}}{\partial PGDP_{it}} = \beta_1 + \sum_{k=1}^{K}\beta_1^k \Gamma^k(IE_{it};.). \tag{2}$$

As shown above, the income elasticity coefficient of pollution emissions is a combination of the linear and non-linear components of the model, which evolves with variations in the transition variable, energy intensity. This study applied non-linear least squares (NLS) to estimate the model parameters, followed by the further computation of the income elasticity coefficient of pollution emissions. For a more concrete overview and details on the testing and estimation of the PSTR model, please refer to González et al. (2005) and Fouquau et al. (2008).

2.2. Descriptive statistics of interregional differences in pollution emissions and energy intensity

The descriptive statistics used in our calculations are presented in Table 1. As shown, emission intensity, per capita GDP, energy intensity, industrial structure, and environmental regulation intensity in the sampling period all depict interregional or temporal differences. In particular, the standard deviations for emission intensity and per capita GDP are relatively large. The maximum value of emission intensity is approximately 1802.889 (Ningxia; 2003) and the minimum value is 8.713 (Shanghai; 2016). The maximum value for per capita GDP is 128,994 (2017, Beijing) and the minimum value is 3701 (Guizhou; 2003). For energy intensity, the maximum and minimum values are 4.689 (Ningxia; 2004) and 0.284 (Beijing; 2016). The maximum and minimum values for the industrial structure are 0.615 (Shanxi; 2008) and 0.143 (Beijing; 2017). For environmental regulation intensity, the maximum value is 2.825 (Beijing; 2017) and the minimum value is 0.127 (Inner Mongolia; 2017).

To gain more comprehensive understanding of interregional and temporal differences in emission and energy intensities, we conducted a comparative analysis of the average levels of the eastern, central, western, and northeastern regions. Owing to space limitations, we selected four representative time points at the early, intermediate, and late stages: 2003, 2008, 2014 and 2017. The statistical results are presented in Table 2. In terms of temporal differences, on both the national and regional levels, emission and energy intensities showed an overall decreasing trend. This implies that China's recent adjustments in industrial structure, progress in technology, and measures for energy conservation and emissions reduction exerted certain effects, leading to increased energy utilization efficiency and overall improvements in pollution emissions. This result is consistent with those of Lin and Du (2014). In terms of interregional differences, China's emission and energy intensities both showed a stepwise decreasing pattern from the western regions to the eastern regions. More specifically, apart from 2003, the average levels of emission and energy intensities in the northeastern region were between those of the eastern and central regions but closer to those of the central regions. The average levels of emission and energy intensities in the central region were similar to the national average. The above results are consistent with those of existing studies, indicating significant interregional differences in China's emission and energy intensities. Since the eastern region was more developed, its pace of industrial structure adjustments and technological progress was more rapid than those of the central and western regions. On the other hand, the central region reported a faster rate than the western region. In addition, because of the vigorous implementation of environmental regulatory strategies in the eastern region, a substantial number of pollution-intensive industries were transferred to the central and western regions. The western region, in particular, witnessed the emergence of a relatively high number of pollution-intensive industries. The joint effect of these two factors led to China's emission and energy intensities illustrating a stepwise decreasing pattern. Furthermore, our results revealed that low pollution emissions were often accompanied by low energy intensity, which is consistent with our initial point of departure. Given these results, we conducted an empirical analysis from an energy intensity perspective to examine the non-linear characteristics of the effect of income on pollution emissions and identify the energy intensity threshold.

3. Empirical analysis of China's environmental Kuznets curve from an energy intensity perspective

3.1. Model testing and estimation results

The PSTR model is a non-linear regression model. Owing to its complexity and dynamics, statistical tests are required to determine whether the data have non-linear characteristics and identify the number of transition functions and location parameters. First, we tested the non-linear characteristics of the calculated data, the results of which are presented in Table 3. As shown, the test results for the Wald, Fisher, and LRT tests all reject the null hypothesis that the model does not have non-linear characteristics (all p-values equal 0). This indicates that our empirical data has non-linear characteristics and the model established in this study is rational.

Second, statistical testing was performed to determine the number of transition functions. Drawing on existing research, the number of transition functions is generally$k = 1 - 2$. Therefore, we tested this study's model and employed the Akaike information criterion (AIC) and Bayesian information criterion (BIC) to determine the optimal number of transition functions. As shown in the test results (Table 4), when $k = 1$ (one transition function), its AIC

Table 1
Descriptive statistics of data used in the model.

Variable	*Y*	*PGDP*	*IE*	*IS*	*ER*
Unit	Ton/RMB 100,000	RMB	10,000 ton of standard coal equivalent/RMB 100,000		RMB 100,000/ton
Average	287.372	26,276.536	1.392	0.368	0.498
Standard deviation	289.236	16,352.430	0.773	0.084	0.271
Maximum	1802.889	128,994.000	4.689	0.615	2.825
Minimum	8.713	3701.000	0.284	0.143	0.127
Sample size	450				

Table 2
Regional statistical comparison for average emission and energy intensities levels.

Region	2003		2008		2014		2017	
	Emission intensity	Energy intensity	Emission intensity	Energy intensity	Emission intensity	Energy intensity	Emission intensity	Energy intensity
Eastern	266.84	1.21	127.14	1.08	60.66	0.83	42.12	0.67
Central	501.62	1.86	234.68	1.63	120.31	1.24	91.33	1.08
Western	827.54	2.49	481.57	2.30	279.70	2.00	187.56	1.86
Northeastern	192.97	1.82	151.81	1.46	83.53	1.10	75.67	0.84
National	505.48	1.79	265.73	1.61	144.27	1.30	98.43	1.14

Note: for units of measure, emission intensity: Ton/100 million Yuan; energy intensity: 10 thousand standard coal equivalent//100 million Yuan.

Table 3
Test results for model's non-linearity.

Statistic	Statistical value
Wald Tests (LM)	79.114 (0.000)
Fisher Tests (LMF)	32.148 (0.000)
LRT Tests (LRT)	90.130(0.000)

Note: The statistics in parentheses are p-values.

Table 4
Test results for the number of transition functions in the model.

Statistic	$k = 1$	$k = 2$
AIC	−3.778	−3.763
BIC	−3.692	−3.617

and BIC statistics were both smaller than when $k = 2$ (two transition functions). Therefore, we selected $k = 1$.

Finally, we determined the number of location parameters in one transition function and the statistical testing results are shown in Table 5. When there is one location parameter, $h = 1$, the values for the LM, LMF, and LRT statistics are all larger than when there are two or more location parameters, $h \geq 2$. Therefore, we selected one location parameter. To summarize the test results, the data used in this study have non-linear characteristics and are suitable for the PSTR model specification, for which we finally selected $k = 1$ and $h = 1$.

Accordingly, we performed a model estimation using NLS, of which the results are shown in Table 6. The overall estimation results showed that the coefficients of the core explanatory variable (per capita GDP) and control variable (industrial structure) were both significant at the 1% level, indicating a good model estimation effect. The coefficient for the linear component of per capita GDP was negative, while that of the non-linear component was positive. This indicates that the effect of increasing income levels on pollution emissions had a certain level of complexity, which required the integration of coefficients for the components of both analyses. Similarly, the coefficient for the linear component of the industrial structure was positive, while that of the non-linear component was negative, suggesting that the effect of industrial structure on pollution emissions involved complex non-linear mechanisms. The intensity of environmental regulations was not significant. This is possible because the current scale of environmental regulations in China is relatively small and the main regulatory measure is not direct governance but the limitation and migration of pollution-intensive industries and enterprises. In particular, a large number of pollution-intensive enterprises in the eastern region have gradually been transferred to the less-developed central and western regions. Therefore, the input of environmental governance at this stage did not have a significant influence on pollution emissions. The estimation result for the location parameter indicates that for the non-linear effect of income levels on pollution emissions, the critical value of energy intensity is 0.9168, that is, when energy intensity is lower than the critical value, the income elasticity of pollution emissions is in the lower regime, whereas when it is higher, the elasticity coefficient is in the upper regime. The estimation result for the smoothness parameter is relatively small (5.0146), indicating that the transition of regression coefficients between the upper and lower regimes is relatively smooth and not an abrupt change.

Table 5
Test results for the number of location parameters in the model.

Statistic	$h = 1$	$h \geq 2$
LM	40.532	13.165
LMF	13.714	4.021
LRT	42.165	13.755

To clearly present the variations in the income elasticity of pollution emissions and further explore whether the EKC exists in China from the energy intensity perspective, we calculated the coefficient range for the income elasticity of pollution emissions in different regimes using equation (2). The maximum value for energy intensity is 4.689 and its corresponding income elasticity of pollution emissions is 2.56. The critical value of transition between upper and lower regimes is 0.9168 and its corresponding elasticity coefficient is 0.62. The minimum value of energy intensity is 0.284 and its corresponding elasticity coefficient is -0.71. In the lower regime, the income elasticity of pollution emissions is within the range of -0.71–0.62. Further calculations indicate that when energy intensity is 0.7670, the income elasticity of pollution emissions is 0, indicating that, 0.7670 is the EKC threshold of energy intensity. When energy intensity is higher than this threshold, the income elasticity of pollution emissions is positive, implying that, the increase in income levels aggravates the degree of pollution emissions. On the other hand, when energy intensity is below the threshold, the income elasticity of pollution emissions is negative. That is, the increase in income levels reduces the degree of pollution emissions. The above-mentioned results demonstrate that China has an inverted U-shaped EKC and its energy intensity threshold is 0.7670. Thus, from an energy perspective, the logic of the EKC is as follows: before exceeding the threshold, the industrial structure was dominated by pollution-intensive industries, the level of production technology was relatively low, energy intensity was relatively high, and income growth led to increased pollution. After exceeding the threshold, as income levels rose, the optimization of industrial structure and advancements in production technology led to reduced energy intensity, thereby lowering pollution levels. Its essence is the transition from an energy-intensive model of economic development with high energy consumption and pollution levels to an eco-friendly one.

3.2. Analysis of provincial and regional differences based on energy intensity heterogeneity

There is significant heterogeneity in the level of economic

Table 6
Model estimation results.

Variable	Linear component		Non-linear component	
Per capita GDP	β_1	$-1.2374^{***}(0.0435)$	β_1^1	$3.9200^{***}(0.0348)$
Industrial structure	β_2	$2.3950^{***}(0.4814)$	β_2^1	$-5.8120^{***}(0.6840)$
Environmental regulation intensity	β_3	0.2570(0.1768)	β_3^1	−0.3481(0.2520)
Location parameter	0.9168			
Smoothness parameter	5.0146			

Note: Numerical values in parentheses are standard deviations. *** indicates the coefficient is significant at a 1% level.

development and energy intensity among various provinces and regions in China. Therefore, to compare the differences in the income elasticity of pollution emissions among regions, we performed a comparative analysis of the time point at which the thresholds of the inverted U-shaped EKC was observed for the 30 provinces and the eastern, central, western, and northeastern regions. The results are presented in Table 7. The table shows that only seven provinces and regions exceeded the EKC threshold of energy intensity within the sample period, which mainly included developed coastal provinces and municipalities: Beijing, Tianjin, Shanghai, Jiangsu, Zhejiang, Fujian, and Guangdong. Among them, Beijing exceeded the threshold at the earliest time point (2007) and Tianjin was relatively late (2014), while the range of time points for the other provinces and regions was 2009–2012. Other areas did not reach the threshold. In terms of regions, the eastern, central, western, and northeastern regions and the national average did not meet the threshold. However, the energy intensity of the eastern region in 2017 approached the threshold, whereas that of the western region was at a level of approximately 2.

The results of the regional differences elucidate that due to the dependence of developed eastern provinces on ports, coupled with support from the reform and opening-up policies, they opened up to the world earlier and had a faster rate of industrial structure adjustments. Moreover, the introduction of new technologies resulted in a higher level of production technology. Therefore, their energy consumption per unit output was relatively low, which led to the rapid decline in energy intensity over the past few years. In this developmental model, some provinces in the eastern region successfully exceeded the EKC threshold, implying that they achieved a win-win situation for both economic growth and environmental protection. Their energy-efficient approach to development promoted the growth of income levels while reducing emission intensity. By contrast, certain areas in the eastern region and the vast majority of the central and western regions reported less advanced economic development with slower adjustments in industrial structure, lower levels of production technology, and lower energy efficiency. In particular, the emission intensity of the central and western regions was significantly higher than that of the eastern region. On the one hand, the economic development of the central and western regions is dependent on industries with high energy consumption and high pollution emissions, while their technological level has a limited effect on improving their energy efficiency in the short run. On the other hand, the eastern region has been transferring pollution-intensive industries to the central and western regions, which also explains the higher energy efficiency of the eastern region compared to the central and western regions. Therefore, some areas in the eastern region and all in the central and western regions exceeded the energy intensity threshold. Without significant improvements in industrial structure and production technology in the future, the rise in these areas' income levels will be unable to effectively suppress pollution emissions. This will lead to a lose-lose situation for both economic growth and environmental protection.

In addition, we found that although certain provinces did not exceed the energy intensity threshold, they did exceed the critical value between the upper and lower regimes (0.9168) for the effect of income levels on pollution emissions. These include Anhui, Jiangxi, and Hainan. Accordingly, we divided the 30 provinces (autonomous regions and municipalities) in our sample into three types: eco-friendly provinces that exceeded the energy intensity threshold (energy intensity < 0.7670), low-pollution provinces that exceeded the critical value between the upper and lower regimes but not the threshold (energy intensity = 0.7670–0.9168), and high-pollution provinces that did not exceed the critical value between the upper and lower regimes (energy intensity > 0.9168). It should be noted that the data used in the present empirical analysis was a major air pollutant, industrial SO_2, and therefore, the results of our division do not represent the emissions of other pollutants. For example, Beijing has a relatively severe PM2.5 pollution level, but it was classified as an eco-friendly province in terms of industrial SO_2 emissions. Furthermore, the criterion for our division was energy intensity, that is, the relative levels of energy consumption and per capita GDP, while emission intensity was measured using the relative levels of industrial SO_2 and VAI. Since these two indicators are not absolute levels, the division results do not represent the absolute levels of pollution emissions, the result of which are summarized in Table 8. Targeted and differential policies for environmental governance should be formulated on the basis of the actual conditions of various regions.

4. Conclusions and policy implication

In the context of developing countries, finding evidence in support of the environmental Kuznets curve hypothesis might have promising implications for sustainable economic growth in the future. This is especially significant for China; the largest emerging economy in the world. This study examined the environmental Kuznets curve (EKC) hypothesis in China and its possible regional differential characteristics based on provincial panel data of 2003–2017, using panel smoothing transition regression (PSTR) model. The findings of the studies show:

First, China's pollution emissions and energy intensities show a stepwise decreasing pattern from the western region to the eastern region. Second, the impact of income levels on pollution emissions is non-linear, and the critical value of energy intensity is 0.9168 between the high- and low regimes. Third, an inverted U-shaped environmental Kuznets curve is accepted for energy intensity, with 0.7670 as its threshold value. When the energy intensity is higher

Table 7
Comparison of years in which regions reached energy intensity threshold.

Region	Beijing	Tianjin	Hebei	Shanxi	Inner Mongolia	Liaoning	Jilin	Heilongjiang	Shanghai
Year	2007	2014	–	–	–	–	–	–	2011
Energy intensity	0.757	0.762	1.459	2.249	1.923	1.197	1.015	1.088	0.719
Region	Jiangsu	Zhejiang	Anhui	Fujian	Jiangxi	Shanxi	Henan	Hubei	Hunan
Year	2012	2010	–	2012	–	–	–	–	–
Energy intensity	0.766	0.767	0.893	0.752	0.809	0.980	1.020	1.103	1.027
Region	Guangdong	Guangxi	Hainan	Chongqing	Sichuan	Guizhou	Yunnan	Shaanxi	Gansu
Year	2009	–	–	–	–	–	–	–	–
Energy intensity	0.744	1.007	0.835	1.110	1.118	2.124	1.423	1.185	1.701
Region	Qinghai	Ningxia	Xinjiang	Eastern	Central	Western	Northeastern	National	
Year	–	–	–	–	–	–	–	–	
Energy intensity	2.966	3.409	2.954	0.803	1.236	1.999	1.100	1.302	

Note: "-" denotes that the area did not exceed the threshold during the sample period.

Table 8
Division of regions as per energy intensity.

Type	Eco-friendly	Low pollution	High pollution
Energy intensity	<0.7670	0.7670−0.9168	>0.9168
Provinces (autonomous regions, municipalities)	Beijing, Tianjin, Shanghai, Jiangsu, Zhejiang, Fujian, Guangdong	Anhui, Jiangxi, Hainan	Hebei, Shanxi, Inner Mongolia, Liaoning, Jilin, Heilongjiang, Shandong, Henan, Hubei, Hunan, Guangxi, Chongqing, Sichuan, Guizhou, Yunnan, Shaanxi, Gansu, Qinghai, Ningxia, Xinjiang

(lower) than the threshold value, the income elasticity of pollution emission is positive (negative). Forth, more developed provinces and municipalities mainly in the eastern region are proved to exceed the threshold than the provinces in the central and western regions within the sample period. Based on this, China's provinces could be categorized by the threshold values of EKC of energy intensity into eco-friendly, low-pollution, and high-pollution provinces.

This study identifies China's EKC threshold from an energy intensity perspective rather than the traditional threshold of income level. Therefore, the policy makers or researchers could understand the EKC characteristics more directly and significantly by its corresponding energy intensities. Besides, the inter-provincial and interregional differences in the EKC threshold of energy intensity are investigated so that environmental governance policies could be administered better within countries with unbalanced development levels in different regions.

Based on the above, this study proposes some environmental governance measures for regional and macro- and micro-level governance.

First, macro-level governance: In terms of the national average level, China's energy intensity remains relatively high and has not exceeded the EKC threshold. Therefore, continuing to follow an extensive model of economic development with high energy consumption will further exacerbate environmental pollution. The general idea of environmental governance at this stage should be to achieve a win-win situation for both economic growth and environmental protection. This should not be achieved through administrative interventions to limit the number of pollution-intensive industries but by enhancing the quality of their development and reducing energy intensity. An intensive model of economic development should be achieved through technological advancements and industrial structure adjustments, thereby maintaining rapid economic growth while reducing energy intensity. This will enable China to exceed the threshold as soon as possible and attain the virtuous cycle of environmental governance driven by economic development.

Second, micro-level governance: In micro-level governance, the starting point should be the promotion of technological advancements and industrial structure adjustments. On the one hand, the “Made in China (2025)” plan should be fully implemented in production industries, especially in pollution-intensive industries. China should continue to introduce and learn more about advanced technologies and experiences from developed countries. Independent research and innovations in green production technology should continue to be strengthened and the upgrading of equipment should be promoted. These measures will help China achieve mid-to high-end green manufacturing. On the other hand, the government should encourage business transformations through marketization. First, the reward criteria should be set as the per energy intensity threshold, which gives eco-friendly enterprises and regions higher financial transfer payments and other incentives. Second, a pollution tax should be levied for high-pollution enterprises, thus “forcing” technological improvements in enterprises and reducing energy intensity. Finally, the development of green finance should be encouraged, which involves guiding credit funds towards eco-friendlier enterprises while providing financial support for the development of green technology in pollution-intensive industries.

Third, regional governance measures: China's emission and energy intensities depicted a stepwise decreasing pattern of decrease from the western to the eastern regions, which in turn, determines the differences in the formulation of environmental governance strategies. In the eastern region, continuing to exert the advantages of industrial structure and technological level in lowering energy intensity will further reduce emission intensity. However, the transfer of pollution-intensive industries from the eastern to the central and western regions, which will undoubtedly aggravate environmental pressure in the central and western regions, should not be encouraged. Instead, technological improvements should be promoted in local pollution-intensive industries to form a green development model. As for the central and western regions, the acceleration of industrial structure adjustments is of utmost importance at the current stage. These regions should take advantage of the development experiences in the eastern region to promote the development of tertiary and eco-friendly industries while undertaking the technological transformation of backward and pollution-intensive industries. Furthermore, as per this study's classification, eco-friendly provinces should undertake the exchange of experiences and technology to provide low- and high-pollution provinces with greater technological support and a reference for the development model.

Though the findings of this study are encouraging, we are still inclined to be prudent, for some of the results are not efficiently analyzed. For example, we would have taken PM2.5, PM10, NOx, apart from SO2, as a comprehensive indicator of environmental pollutants to make our research more convincing but failed because of the availability and inconsistency of the relevant data. Besides, we need to further extend our study in the future to investigate more general but specific features among individual countries at similar levels in concerning indicators. We also need more advanced techniques to capture catching-up characteristics between countries at different economic development stages.

Acknowledgment

The paper is supported by Report Series from Ministry of Education of China (No. 10JBG013), China National Social Science Fund (No. 17AZD013), Shanxi Soft Science Program (2018041004-2), Shanxi Planning Project of Philosophy and Social Science (Jin P.[2016]No.2), the Philosophy and Social Science Research Project for Higher Education (Jin ES.[2015]No.26), China National Natural Science Fund (No. 71774105), the National Science Foundation of China (No. 71701176, 15ZDA015, 71804063, 71433005), SXUFE Teaching Reform Project (2016103), and MOE (Ministry of Education in China) Project of Humanities and Social Science (18YJC630208).

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