Analysis of environmental regulation and total factor energy efficiency

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This present article proposes a mechanism and mathematical model of environmental regulation and energy efficiency. Then, it analyses the panel data of 30 provinces in China from 2000 to 2012 by using the super-efficiency DEA model. Empirical results show that, in general, environmental regulation can significantly promote the total factor energy efficiency in China, which is an existing reversed transmission mechanism. There are obvious U-structure nonlinear relations between environmental regulation and total factor energy efficiency. Most of the eastern provinces of China are on the right side of the U-structure's inflection point. Therefore, energy efficiency can be improved by promoting environmental regulation. However, the central and western provinces are primarily on the left side or near the U-structure's inflection point. In these regions, environmental regulation does not implement the reversed transmission mechanism. The differences between developed provinces and undeveloped ones contribute to realizing the plight in the development stages of emerging market countries.

Keywords: Environmental regulation, total factor energy efficiency, U-structure.

CHINA'S economy has seen rapid growth for nearly 30 years, at the cost of energy and environment. According to the British Petroleum (BP) Statistical Review of World data, China's energy consumption represented 21.9% of the world's consumption in 2012, whereas the energy consumption in America and the European Union was 17.7% and 13.4% respectively. China has become the world's largest energy consumer. In addition, China's coal consumption represented approximately 70% of the total consumption. Oil imports are increasing at an annual rate of 10%. China's per capita CO_2 emissions were as high as 7.2 tonnes in 2013. China has already become the world's largest CO_2 emitter. Rapid economic growth and predatory exploitation make China's ecological environment pay a heavy price. China has become one of the most polluted countries in the world. In the first three years of China's 12th five-year plan, the unit GDP energy consumption had completed 54.3% of the five-year task, which is far from the scheduled target of 60%. The realization of energy conservation and a reduction in polluting emissions have become an increasingly important part of China's economic development strategy. As the largest developing country, China's experiences are being studied by other developing countries and emerging market countries for reference.

The world, in the process of industrialization, has consumed a large quantity of energy and has wrought increasingly serious environmental problems since the 1970s. Countries have gradually focussed more on protecting the environment. Environmental pollution prevention has been a major method to protect the environment. Currently, controlling the total amount of environmental pollution serves as the main active regulation, which, to an extent, effectively prevents environmental degradation. For a long time, environmental regulation has been considered as the duty of the government, whereas improving energy efficiency has been considered the duty of enterprises. The influence of environmental regulations enacted for energy efficiency is characterized by its effects on the behaviour of the enterprise. On the one hand, environmental regulation made enterprises pay money to control pollution emission, which increases production cost, thereby reducing production efficiency. This view, called the 'compliance cost', conforms to the method of analysis in traditional economics. Early academic scholars support the compliance view[1–3]. On the other hand, reasonable environmental regulation can form a reversed transmission mechanism, which will stimulate enterprises to innovate. Innovation can not only offset the negative effects due to higher costs but also promote the technological progress and industrial structure upgrade. Thus, environmental regulation can improve the production efficiency and competitiveness. This view called 'innovation compensation'[4–9] has found much support. Chinese academic scholars also focus more strongly on environmental regulation problems. Most Chinese researchers focus on the effect that environmental regulation has on production and technical efficiency. Zhang and Xia[10] found that there was a U-shaped relation between environmental regulation and the technical efficiency in power generation industry by using a Stochastic Frontier

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Analysis (SFA) model. Li *et al.*[11] estimated the impact of environmental regulation intensity on China's economy, including economic growth, manufacturing employment, and exports, using a Computational General Equilibrium (CGE) model. However, the question arises as to whether environmental regulation generates an effect similar to the 'porter hypothesis' on energy efficiency when the environmental regulation becomes stronger. Chen and Zhang[12], by an empirical study, found that environmental regulation had a significant effect on China's total factor energy efficiency. Bi *et al.*[13] utilized the data envelope analysis (DEA) and found that environmental efficiency could significantly affect the energy conservation situation of China's thermal power industry. The foregoing review shows that studies are not adequate to examine the relation between the total factor energy efficiency and environmental regulation intensity; it remains to be studied further. According to this study and China's realities, there are three questions to be answered: (i) Does China's environmental regulation promote or inhibit energy efficiency in general? (ii) As the environmental regulation intensity changes, does it impact energy efficiency in the long run? Is it a simple linear relation? (iii) Do environmental regulation and the total factor energy efficiency present obvious nonlinear U-structures? Main objective of the present article is to analyse the third question.

Methods

Mechanism

Environmental regulations are policies and measures formulated by the government to address the external diseconomy. Environmental regulation could suit the economic activities of enterprises, maintain the environment in harmony with the economic development and can coordinate and enforce environmental polluters and stakeholders to fulfill their environmental responsibilities and obligations. Environmental regulation can have a direct or indirect influence on energy efficiency; its mechanism is mainly embodied in three aspects: (i) Under the premise of technology, resource allocation and fixed consumer demand, production level of the enterprises achieves equilibrium. With the introduction of environmental regulation, enterprises must spend money on pollution prevention or pay for pollution taxes, which will increase the production cost. In addition, with the increment of intensity of environmental regulation, cost for pollution treatment increases gradually. This, to a certain extent, affects the production investment, resulting in a decrease in production level by the enterprise. If the energy input remains stable or increases, the energy efficiency will be reduced. (ii) Environmental regulation leads to additional costs that affect the competitiveness in the market. Therefore, to remain ahead in the market share, enterprises must improve their technical efficiency. Energy consumption and pollution emissions are often closely related, which will promote enterprises to improve technology using reversed transmission mechanism, thus promoting energy efficiency. (iii) Environmental regulation requires enterprises to comply with certain environmental standards. Energy-intensive and high-emission enterprises that do not meet the requirements of strict environmental standards will gradually become

obsolete. These enterprises must adopt new cleaner production technologies to implement the industrial development transformation and upgrade. Furthermore, new enterprises entering production are usually required to install advanced energy-saving and pollution-controlling equipment. The government also establishes stricter anti-pollution standards for new enterprises to form a type of barrier. This type of regulation is called 'grandfather rules'; its target is to make new enterprises attain higher energy efficiency and reduce pollution. The environmental regulation mechanism pertaining to energy efficiency is shown in Figure 1.

Mathematical model

Consider a manufacturer who needs to put in energy materials that produce certain pollution emissions under an imperfect, competitive market structure. The Dixit and Stiglitz Framework (D–S framework) conforms to the market environment that the manufacturer with a certain monopoly ability is encountering[14]. Before analysing, we first propose a basic market hypothesis and the manufacturer's production status.

Assuming that there is a continuous commodity bundle Ω in the market. The consumer's utility function with constant elasticity of substitution (CES) is $U = (\int_0^n q(i)^\rho \, \mathrm{d}i)^{1/\rho}$, where n denotes the types of consumer goods in the market, $q(i)$ denotes the consumption quantity of the ith commodity, and parameter ρ denotes the inclination coefficient of diversity, $0 < \rho < 1$. If $\rho \to 1$, the utility function is a linear function. If $\rho \to 0$, the consumer's diverse preference degree is large, and more the types of consumer goods, the greater is the effect. If $\sigma = 1/(1-\rho)$, σ is the elasticity of substitution between any two commodities. Therefore, the consumption quantity indicators are $Q = (\int_0^n q(i)^{(\sigma-1)/\sigma} \, \mathrm{d}i)^{\sigma/(\sigma-1)}$ when the degree of differentiation among commodities is continuous. Furthermore, we assume that $p(i)$ is the price of different goods. According to Dixit and Stiglitz[15], the price index of a commodity bundle is $P = (\int_0^n p(i)^{1-\sigma} \, \mathrm{d}i)^{1/(1-\sigma)}$. The demand quantity of the ith commodity is

$$q(i) = Q(p(i)/P)^{-\sigma}. \tag{1}$$

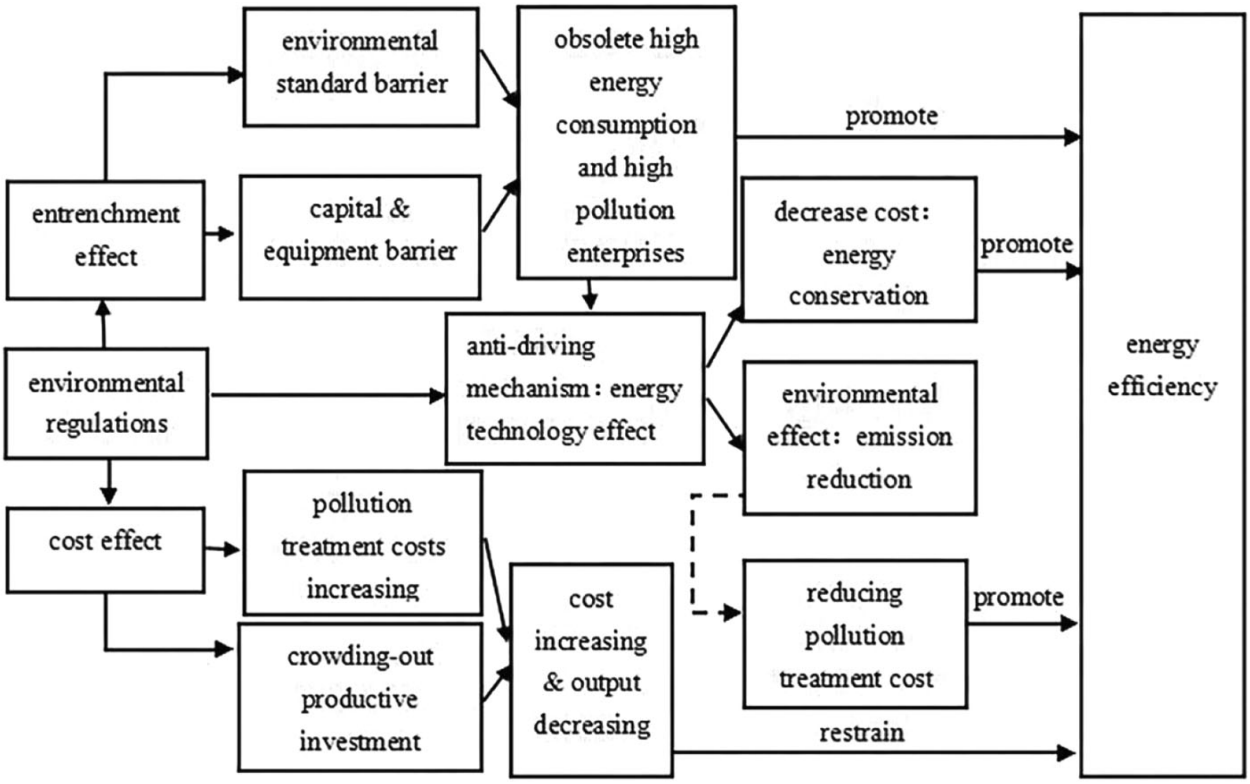

Figure 1. Mechanism of the environmental regulation made on energy efficiency.

The total expenditure of the consumer is $R = PQ = \int_{i\in\Omega} r(i)\mathrm{d}i$, where $r(i)$ is the consumer expenditure of the ith commodity. Its formula is

$$r(i) = p(i)q(i) = PQ(p(i)/P)^{1-\sigma} = R(p(i)/P)^{1-\sigma}. \quad (2)$$

The above content simply analyses the market demand characteristics which the manufacturer faces in monopolistic competition market. This article mainly considers manufacturer's production behaviour in terms of energy usage. We assume that there is only one variable input, energy E, owned by the manufacturer and the researched manufacture's energy efficiency is ε. The energy efficiency is the only difference among different manufacturers while other aspects are homogeneous. Therefore, the manufacturer's output is q, the variable cost is q/ε and f denotes fixed cost. The total cost is $c = f + q/\varepsilon$. The manufacturer has monopoly characteristics, but the production department of the manufacturer is not a natural monopoly. The government has no franchise production department. This implies that there are many potential entrant-enterprises in the market. If the monopoly manufacturer sets price at p, these entrant-enterprises will enter the market at the price of $p - \mu$ (μ is a very small number) to take away the monopolistic market. Therefore, the manufacturer cannot set the price according to monopoly price. The optimal pricing strategy is marginal cost plus pricing. That is to say, the market behaviour of the manufacturer is the same as the manufacturers in the perfectly competitive market. Here, the optimal price of the manufacturer is

$$p_i = 1/\rho\varepsilon_i. \quad (3)$$

Due to the manufacture's production process, it will bring certain pollution emissions ψ; its negative externality created the governmental environmental regulation. These environmental regulations make the manufacture's pollution emission to be under a certain level $\psi \le R$, R is the maximum pollution emission permitted by the government, which is also called environmental regulation intensity. To control pollution emission within the environmental regulation, manufacturers will adopt two methods. First, manufacturers can invest at the end of chain of pollution control to make the pollution emission level meet the requirements of environmental regulation. We assume that the annual operational capital is k_a, and $k_a'(R) > 0$, which means that with improving environmental regulation intensity, the manufacturer will have to invest more money on pollution control. Second, we assume that the pollutants mainly come from the high energy consumption of extensive production pattern. The manufacturer can use cleaner technology and optimize the energy structure to improve energy efficiency to reduce the pollutants from the source. However, this way needs the manufacturer to modify the existing energy utilization method and technology and invest k_{b}, and $k_{\mathrm{b}}'(R) > 0$, which means that the investment fund is directly proportional to the environmental regulation intensity. In addition, the improvement of energy efficiency contributes to reducing the energy consumption and pollution emissions. It is a dual role. We use $\phi(e_i, \gamma_i)$ to denote the improving economic effect of manufacturers, which benefits from increasing of energy efficiency. Here e_i is the ith manufacturer's energy consumption; γ_i denotes the reduced pollution emissions. Through these two approaches, the profit which manufacturers can obtain are

$$\pi_i^1 = (R/\sigma[P\rho\varepsilon_i]^{\sigma-1}) - f - k_{\mathrm{a}}(q_i, R). \quad (4)$$

$$\pi_i^2 = (R/\sigma[P\rho\varepsilon_i]^{\sigma-1}) - f - k_{\mathrm{b}}(R, e_i) + \phi(e_i, \gamma_i). \quad (5)$$

Profit maximization is the goal of manufacturers. The profit level under two types of decisions affects the manufacturers' behaviour while facing the environmental regulation. In general, $k_{\mathrm{a}}(q_i, R) < k_{\mathrm{b}}(R, e_i) - \phi(e_i, \gamma_i)$ is necessary to make the manufacturers control discharge of pollutants. In reality, manufacturers usually take the first approach, particularly the low energy consuming industrial manufacturers. By strengthening environmental regulation, manufacturers focus more on the condition of future profits rather than current earnings. Therefore, the manufacturers' production decision depends on eqs (6) and (7) in the time period τ.

$$\pi_i^{1'} = \int_\tau \{(R/\sigma[P\rho\varepsilon_i]^{\sigma-1}) - f - k_{\mathrm{a}}(q_i, R). \quad (6)$$

$$\pi_i^{2'} = \int_\tau \{(R/\sigma[P\rho\varepsilon_i]^{\sigma-1}) - f + \phi(e_i, \gamma_i)\} - k_{\mathrm{b}}(R, e_i). \quad (7)$$

Under the government formulated environmental regulation, there are only two approaches for the manufacturers to choose. The first one is to spend some part of the cost towards pollution treatment every year. The second one is a one-time investment in technical renovation to improve the energy efficiency and reduce the pollution emission, then obtain economic effect in the subsequent production. q, e and γ in eqs (6) and (7) are endogenous variables. Their relative sizes are influenced by specific industrial characteristics and environmental regulation intensity. If $\pi_i^{1'} > \pi_i^{2'}$, for the ith manufacturer, environmental regulation increases a part of pollution treatment cost, and the energy consumption is not affected. The relative energy efficiency decreases when the level of profits falls. If $\pi_i^{1'} < \pi_i^{2'}$, the ith manufacturer would like to choose the second method, while the energy consumption decreases and the energy efficiency increases. Therefore, the relationship of value between $\pi_i^{1'}$ and $\pi_i^{2'}$ will vary with the intensity of environmental regulation. On the basis of the analysis, we propose the following:

Proposition 1: The government's environmental regulation can affect the energy efficiency of manufacturers. As both promotion and inhibition effect possibilities exist, the impact of the final result depends on the combination of both positive and negative effects.

Proposition 2: With the strengthening of the environmental regulation intensity, the pollution treatment cost of manufacturers will rise, which will increase the stimulating effect of the enterprise to improve energy efficiency. In the long run, manufacturers react differently to different intensities of regulation, because various environmental regulations can create different impacts on manufacturers. Therefore, the energy efficiency level may be changed with the environmental regulation intensity, which is not a simple linear relation.

Methodology

Data envelopment analysis method, a well-established non-parametric approach, has been widely used to evaluate the relative efficiency of a set of comparable entities called decision-making units (DMUs) with multiple inputs and outputs[14]. In this article we apply Malmquist index method to measure the total factor energy efficiency of China's 30 provinces, based on DEA. As the model can only work out the efficiency variability index of the current year with reference to the previous year, it yields relative variation. Therefore, in order to get the total factor energy efficiency of the base year, we adopt super-efficiency DEA model, which is suitable for the cross-sectional data to measure energy efficiency. Meanwhile, we analyse the impacts that environmental regulations made on the total factor energy efficiency based on the model measuring results.

(1) Super-efficiency DEA model: Traditional DEA model can get relative efficiency values from different DMUs. However, several DMUs that are effective in traditional DEA model, do not represent that they are in the same level of efficiency. To distinguish the effectiveness among them, the traditional DEA model is developed into super-efficiency DEA model which is suitable for ordering a number of DEA effective decision making units at the same time. The basic idea of super-efficiency DEA model is that, when evaluating a decision making unit, the decision making unit excludes itself from DMU-set. The linear programing model can be shown as

$$\text{Min}[\theta - \varepsilon(\hat{e}^T S^- + e^T S^+)]$$

$$\text{s.t.} \sum_{j=1, j\neq k}^{n} X_j \lambda_j + S^- = \theta X_k,$$

$$\sum_{j=1, j\neq k}^{n} Y_j \lambda_i - S^+ = Y_k,$$

$$\delta_1 \left(\sum_{j=1}^{n} \lambda_i + \delta_2 (-1)^{\delta_3} \lambda_{n+1} \right) = \delta_1,$$

$$\lambda_j \geqq 0, S^- \geq 0, S^+ \geq 0, j = 1, 2, ..., n, n+1. \tag{8}$$

Compared with the traditional DEA model, when the super-efficiency DEA model evaluates the *k*th DMU, the *k*th DMU does not identify itself as establishing the frontier production function but is replaced by the linear combination of input–output data of other DMUs. Therefore, the original DMU on the DEA frontier can make its input increase in proportion to the constant efficiency value. The input increasing ratio is its super efficiency evaluation value.

(2) Malmquist index: Malmquist index is a method of productivity measurement and decomposition, which is suitable for panel data. Malmquist index can estimate the total factor productivity change indexes of different units and break them up into technical progress efficiency and rate of technical efficiency changes (including pure technical efficiency and scale efficiency changes). On the premise of setting industrial sector of a certain province as a decision making unit, (x_t, y_t) denotes the inputs and outputs in time period t. (x_{t+1}, y_{t+1}) denotes the inputs and outputs in time period $t + 1$. $D_0^t(x_t, y_t)$ and $D_0^{t+1}(x_{t+1}, y_{t+1})$ are output distance functions, according to the production site at the same time period $(t, t + 1)$ respectively, which is achieved by comparing with the frontier technology. $D_0^t(x_{t+1}, y_{t+1})$ and $D_0^{t+1}(x_t, y_t)$ are output distance functions, according to the production site during mixing time period, which is got by comparing with frontier technology. Based on the research carried out by Färe *et al.*[16], Malmquist index can be further decomposed as

$$M_0(x_t, y_t, x_{t+1}, y_{t+1})$$

$$= \frac{S_0^t(x_{t+1}, y_{t+1})}{S_0^t(x_{t+1}, y_{t+1})} \times \frac{D_0^t\left(x_{t+1}, \dfrac{y_{t+1}}{\text{VRS}}\right)}{D_0^t\left(x_t, \dfrac{y_t}{\text{VRS}}\right)}$$

$$\times \left[\frac{D_0^t(x_{t+1}, y_{t+1})}{D_0^{t+1}(x_{t+1}, y_{t+1})} \times \frac{D_0^t(x_t, y_t)}{D_0^{t+1}(x_t, y_t)} \right]^{1/2}$$

$$= Sech \times Pech \times Techch = \text{TFP}, \tag{9}$$

Here, TFP represents the total factor productivity index; *Sech* is the scale efficiency change index; *Pech* is a pure technical efficiency change; *Techch* is the technical change index. If $M_0(x_t, y_t, x_{t+1}, y_{t+1}) > 1$, the efficiency level of the current period improves compared to the last period, and vice versa. The index TFP is the total factor energy efficiency, which will be studied here.

(3) The setting of the econometric model: To test proposition 1, we studied the fundamental direction that the environmental regulation intensity made on energy efficiency. With changing the environmental regulation intensity, the influence on energy efficiency may become complex. This study uses the quadratic lines analysis of environmental Kuznets curve for reference and conducts a further empirical test by introducing quadratic term of environmental regulation intensity. The measurement equations are established as

$$\text{TFEE}_{it} = \alpha_0 + \alpha_1 \text{ERI}_{it} + \alpha_k \sum X_{it} + V_i + \mu_{it}. \tag{10}$$

$$\text{TFEE}_{it} = \beta_0 + \beta_1 \text{ERI}_{it} + \beta_2 \text{ERI}_{it}^2 + \beta_k \sum X_{it} + V_i + \mu_{it}. \tag{11}$$

TFEE_{it} denotes the total factor energy efficiency of i region in year t. ERI_{it} represents the environmental regulation intensity of i region in year t. According to the factors which influence China's total factor energy efficiency, this article chooses k control variable. GDPP_{it} represents the economy development level of i region in year t. PRO_{it} denotes property right structure of industrial sector of i region in year t. ESTR_{it} is the energy consumption structure of i region in year t. STR_{it} denotes the level of industrialization of i region in year t. β_0 is intercept term which does not vary with the individual. V_i is individual effect. μ_{it} is random error term.

Data

China's 30 provinces, autonomous regions and municipalities directly under the central government (not including Hong Kong, Macao, Taiwan and Tibet) as research objects for the period 2000–2012 have been selected for the study. Measuring the process of total factor energy efficiency in these regions, three input factors (capital stock, labour and energy consumption) and one output factor (regional GDP) have been chosen. The capital stock data are obtained by the perpetual inventory method. We assume that the capital depreciation rate is 10.96%. According to the corresponding price index of investment in fixed assets, the capital stock data are all converted to the level of 2000. Labour indexes are generally measured by labour time. Here, due to the data access, we have selected the number of people employed at the end of each year from different provinces and regions to measure labour indexes. Energy consumption is total energy consumption of the provinces or regions (converted to standard coal).

Selecting the environmental regulation variables is the basis of this empirical study; however, in reality, there are no fixed modes of government intervention and independent regulation tools, which cause great difficulties in measurement. After comprehensive consideration, this work chooses changes of pollutant discharge amount to characterize the environmental regulation intensity. Considering that industrial sectors are the main sources of environmental pollution and energy consumption, the regional environmental regulation on industries can nearly represent the overall environmental regulation intensity in the region. We have chosen industrial waste gas, waste water and industrial waste solid emissions to construct regional environmental indicators of environmental regulation intensity. To avoid the high correlation among these different pollutant emissions and measurement differences among different pollutants, this article needs to build a comprehensive indicator measurement system. The relative indicators are constructed as

$$\mathrm{eri}_{ijt} = \frac{p_{ij}}{\frac{1}{30}\sum_{i=1}^{30} p_{ij}} \quad j = 1, 2, 3, \tag{12}$$

Here, p_{ij} represents the ratio of industrial added value of i region and the jth kind of pollution discharge amount (the industrial added value of all regions are converted into 2000 level). The value of eri_{ijt} reflects the relative ratio of unit value added of jth pollution discharge amount in i region and the nationwide total. eri_{ijt} is a dimensionless variable. Therefore, we can make sum and average as

$$\mathrm{ERI}_{it} = \frac{1}{3}(\mathrm{eri}_{i1t} + \mathrm{eri}_{i2t} + \mathrm{eri}_{i3t}). \tag{13}$$

ERI_{it} denotes the comprehensive environmental regulation intensity of i region in year t. ERI_{it} represents the relative unit output value of the industrial pollution emission in a region compared to the level nationwide. The region with lower industrial pollution emissions and higher industrial added value has stronger environmental regulation intensity. The remainder of the four control variables are GDPP_{it}, PRO_{it}, ESTR_{it} and STR_{it}. GDPP_{it} denotes economic development level, which is represented by the constant GDP per capita (in log) of a region. $\mathrm{PRO}_{\mathrm{it}}$ denotes the property right structure of the industrial sector, which is measured by the ratio of the total value of state-owned and state holding enterprises output and the scalable industrial output value. $\mathrm{ESTR}_{\mathrm{it}}$ is the energy consumption structure, which is represented by the coal consumption proportion in the total energy consumption. The level of industrialization, STR_{it}, is represented by the proportion of a region's industrial added value in GDP. Certain factors change over time, such as energy price, changes in energy conservation and emissions reduction technologies, energy conservation and emission reduction polices. The influence of these time-unobserved effects on each region is similar, whereas the degree may be slightly different. We control the effects of the change by introducing a time variable, TIME. In addition, the level of economic development generally represents the regional technology level and industry distribution. Therefore, to control the comprehensive effect that the economy development made on energy efficiency, we introduce the square to control the likely impact of a non-linear effect. All of the data of the above variables involved originate from the China statistical yearbook, China energy statistical yearbook, China compendium of statistics 1949–2008, China industry economy statistical yearbook and the statistical yearbook of each province.

Results

Basic analysis of China's provincial energy efficiency

Based on the above mentioned calculation methods, we have obtained the total factor energy super efficiency values of China's 30 provinces and regions in 2000 and the energy efficiency Malmquist growth index from 2001 to 2012. The calculation results of total factor energy efficiency values of all provinces and regions are presented in Table 1. It can be observed that China's overall total factor energy efficiency presents a declining trend. The total factor energy efficiency value continues decreasing from 2000 to 2005. Thereafter, the value rises slightly from 2005 to 2008 and then decreases year by year. The downward trend is closely related to China's macroeconomic environment. The increase in speed of energy efficiency had not maintained pace with the rapid economic growth after 2000. Under the influence of the world financial crisis in 2008, the energy efficiency showed a decline again.

The result of energy efficiency change in China's provinces is similar to most of the conclusions that the energy efficiency level of eastern provinces is far higher than the central and western provinces. The five highest energy efficiency provinces in 2012 were Shanghai (2.216), Beijing (1.698), Guangdong (1.310), Zhejiang (1.251) and Tianjin (1.245), which are all in the eastern developed region. The five lowest energy efficiency provinces in 2012 were Ningxia (0.355), Qinghai (0.361), Guizhou (0.401), Gansu (0.411) and Yunnan (0.422), all of which belong to the less developed western region. Furthermore, the highest energy efficiency could be nearly 6 times that of the lowest. Therefore, China not only has an overall

Table 1. The total factor energy efficiency of China's 30 provinces (2000–2012)

Province	2000	2005	2010	2011	2012	Province	2000	2005	2010	2011	2012
Anhui	0.786	0.748	0.652	0.668	0.686	Jilin	0.838	0.711	0.638	0.652	0.689
Beijing	0.931	1.135	1.508	1.629	1.698	Jiangsu	0.839	0.826	1.037	1.064	1.099
Chongqing	0.654	0.555	0.589	0.561	0.579	Jiangxi	0.907	0.712	0.845	0.855	0.908
Fujian	1.125	0.970	1.152	1.176	1.223	Liaoning	0.866	0.926	0.805	0.760	0.717
Gansu	0.844	0.684	0.505	0.458	0.411	Ningxia	0.523	0.413	0.388	0.376	0.355
Guangdong	1.155	1.221	1.284	1.301	1.310	Qingdao	0.539	0.431	0.407	0.390	0.361
Guangxi	0.851	0.754	0.521	0.562	0.574	Shandong	0.773	0.696	0.663	0.632	0.613
Guizhou	0.654	0.535	0.481	0.446	0.401	Shanxi	0.748	0.713	0.516	0.497	0.461
Hainan	0.858	0.813	0.918	0.875	0.893	Shananxi	0.665	0.589	0.489	0.501	0.510
Hebei	0.777	0.751	0.536	0.512	0.478	Shanghai	1.134	1.490	2.144	2.105	2.216
Henan	0.860	0.767	0.501	0.501	0.514	Sichuan	0.743	0.707	0.552	0.531	0.501
Heilongjang	0.824	0.858	0.720	0.694	0.645	Tianjin	0.883	1.081	1.337	1.176	1.245
Hubei	0.728	0.667	0.547	0.521	0.488	Xinjiang	0.658	0.696	0.725	0.700	0.659
Hunan	0.942	0.845	0.645	0.595	0.543	Yunnan	0.721	0.634	0.486	0.468	0.442
Inner Mongolia	0.951	0.734	0.675	0.654	0.630	Zhejiang	0.828	0.936	1.175	1.198	1.251
National average	0.820	0.787	0.781	0.769	0.770						

Source: Calculated according to the statistical data.

low energy efficiency but also a serious regional imbalance.

Empirical results and analysis

We use a static panel data model to conduct empirical analysis. Considering that there is a certain lag phase of the energy efficiency improvement of enterprises responding to the environmental regulation intensity, to avoid the endogenous problem of explanatory variables caused by their bidirectional relation and to ensure that the energy efficiency of the current period cannot affect the environmental regulation intensity of the last period, this article processes the environmental regulation intensity variable lagging one period.

Before performing a parameter estimation, we first need to choose the appropriate model from fixed effect estimation model and random effect estimation model. We need the intercept item to reflect certain individual characteristics. There is also a certain correlation between intercept item and explanatory variables. From a qualitative perspective, we chose the fixed effect estimation model. By conducting a Hausman test, we also find that the fixed effect estimation model is superior to the random effect model. To solve the residual heteroskedasticity and autocorrelation problem, we adopt the feasible generalized least squares (FGLS) to ensure the robustness of both the fixed effect model and the random effect model in the specific estimation process. Table 2 presents the estimation results.

Models 1 and 2 examine the direction of influence that the environmental regulation intensity made on total factor energy efficiency. Models 3 and 4 test the nonlinear impact. Because the fixed effect model is better, we mainly focus on the estimation results of models 2 and 4. The regression coefficient of ERI is a positive number at 5% significance level, which indicates that China's environmental regulation has a reversed transmission mechanism on the total factor energy efficiency. The first degree term and the quadratic term of $GDPP_{it}$ are statistically significant, and the coefficient of the quadratic term is positive, which illustrates that there is a significant U-structure between economic development level and regional energy efficiency. This result also indicates that introducing the square of regional per capita GDP as a control variable is reasonable. The coefficient of the level of industrialization STR_{it} is positive which indicates that China's energy efficiency of industrial sectors is improved. The positive coefficient of time variable also indicates that China's energy conservation and emission reduction policies played a significant role in recent years. In the nonlinear test of model 4, the coefficient of an item of ERI is negative, whereas the coefficient of the quadratic term is positive. These coefficients are both statistically significant, which indicates that there is a U-structure relation between the environmental regulation intensity and the total factor energy efficiency. With an increase in the environmental regulation intensity, China's total factor energy efficiency decreases at first and then rises, with the inflection point at 2.9774. The results of other control variables in model 4 are similar to those in model 2. In general, the energy consumption structure and industrial property rights structure have an adverse effect on energy efficiency. The higher proportion of coal in energy means a greater proportion of state-owned economy in China's industry, which results in lower energy efficiency in the region. However, the two variables failed to pass the significance test.

Now that the relation between the environmental regulation intensity and the total factor energy efficiency is characterized by U-structure, we need to further analyse

Table 2. Static panel equation estimation results

Explanatory variable	Model 1: Random effect	Model 2: Fixed effect	Model 3: Random effect	Model 4: Fixed effect
ERI	0.0134*** (5.17)	0.0105** (2.39)	–0.0098* (–1.90)	–0.0246*** (–3.09)
ERI^2			0.0028*** (4.04)	0.0041*** (5.22)
GDPP	–2.7167*** (–13.02)	–3.3893*** (–15.57)	–2.6628*** (–11.53)	–2.9114*** (–7.83)
$GDPP^2$	0.1533*** (13.78)	0.1477*** (13.57)	0.1486*** (12.29)	0.1270*** (6.55)
ESTR	–0.0217 (–1.31)	–0.0093 (–0.67)	–0.0543*** (–3.11)	–0.0005 (–0.02)
PRO	–0.0176*** (–2.81)	–0.0018 (–0.15)	–0.0393** (–2.75)	–0.0057 (–0.57)
STR	–0.0002 (–0.68)	0.0016*** (3.48)	0.0000 (0.09)	0.0014*** (4.98)
TIME	–0.0286*** (–8.63)	0.0573 (–0.15)	–0.0264*** (–7.05)	0.0476*** (10.56)
Constant term	70.0425*** (10.28)	–95.7118*** (–9.53)	65.6659*** (8.61)	–78.5275*** (–8.39)
Wald test	509.00	1069.42	320.21	14814.70
Hausman test	150.76		112.86	
Inflection point			1.7705	2.9774
Obs	360	360	360	360

*,**,***: 1%, 5% and 10% significance level respectively. The values in brackets are *t*-test values of the regression coefficient.

Figure 2. Distribution diagram of provincial average environmental regulation intensity in China.

the different stages. The distribution of the average environmental regulation intensity of China's 30 provinces from 2000 to 2012 is shown in Figure 2. As we can observe, the provinces on the right side of the inflection point are mostly in the eastern region. Central provinces are mainly distributed near the inflection point. The western provinces are mainly located on the left side of the inflection point. Therefore, strengthening the environmental regulation intensity of the eastern provinces can further improve energy efficiency, whereas the environmental regulation of the central and western provinces does not promote an increase in the energy efficiency. The reason is that the polluting industries of eastern provinces transfer to the central and western provinces under the stronger environmental regulation of the eastern provinces. Therefore, the central and western provinces need to further optimize the environmental regulation design in conformance with their own characteristics.

Relevant research has mainly adopted the static panel model to conduct empirical analysis; however, in many cases, any change in economic factors has a certain inertia within. That is, the previous results tend to have a certain influence on the following period. The total factor energy efficiency of China's provinces is likely to have a hysteresis effect. Therefore, to obtain more robust analysis results, we introduce the lag explained variable as the explanatory variable in eqs (10) and (11). The dynamic panel models are presented as

$$\mathrm{TFEE}_{it} = \alpha_0 + \gamma \mathrm{TFEE}_{i,t-1} + \alpha_1 \mathrm{ERI}_{it} + \alpha_k \sum X_{it} + V_i + \mu_{it}. \tag{14}$$

$$\mathrm{TFEE}_{it} = \beta_0 + \gamma \mathrm{TFEE}_{i,t-1} + \beta_1 \mathrm{ERI}_{it} + \beta_2 \mathrm{ERI}_{it}^2 + \beta_k \sum X_{it} + V_i + \mu_{it}. \tag{15}$$

Here, $\mathrm{TFEE}_{i,t-1}$ is the first-lagged dependent variable. γ is regression coefficient.

Introducing the lag term into the dynamic model can better control the lag factors but will also lead to a potential endogenous problem of dependent variables in the model. That is, the dependent variable has a bidirectional causality relation with the explained variable, which will lead to the dependent variable relating to the random disturbance term. Therefore, whether using the least square method, the fixed effects or the random effects, the estimation results are biased. Now we need to apply the difference GMM (DIFF-GMM) or the system GMM (SYS-GMM) estimation method. We adopt both methods to estimate and compare the results.

If the estimated value of GMM is between the fixed effect estimation value and the pooled OLS estimation value, the GMM estimation results are reliable. This is because, the pooled OLS estimation results usually have upward bias and the fixed effect estimation results have downward bias in the short panel. As can be observed from Table 3, the estimation coefficient of the lagged term is between the pooled OLS estimation value and the fixed effect estimation value, which conforms to the effectiveness standard of GMM. In addition, the results of the Sargan test indicate that there is no instrumental variable that excessively recognizes each model. The Arellano-Bond AR(1) test rejects the null hypothesis, whereas the AR(2) test accepts the null hypothesis. This result indicates that the residual sequence of the original equation is uncorrelated and that the instrumental variables are effective. Therefore, the generalized moment estimation results of the two-step difference model and system model are valid and reliable. The first-lagged TFEE in all models passes the 1% significance test, which indicates that there is inertia in China's total factor energy

Table 3. Dynamic panel equation estimation results

Explanatory variable	Model 5	Model 6	Model 7	Model 8	Model 9	Model 10	Model 11	Model 12
	Pooled OLS	Fixed effect	Diff-GMM	Sys-GMM	Pooled OLS	Fixed effect	Diff-GMM	Sys-GMM
L.TFEE	0.9983***	0.8678***	0.8969***	0.9451***	0.9937***	0.8455***	0.8715***	0.9392***
	(74.89)	(19.02)	(36.12)	(91.60)	(74.39)	(19.98)	(31.30)	(67.83)
ERI	0.0007	0.0082**	0.0112***	0.0030[a]	–0.0107**	–0.0151	–0.0207***	–0.0115**
	(0.34)	(1.98)	(7.40)	(1.48)	(–2.13)	(–1.53)	(–4.29)	(–2.06)
ERI^2					0.0015**	0.0032**	0.0032***	0.0016**
					(2.48)	(2.46)	(6.21)	(2.40)
GDPP	–0.2194***	–0.3142**	–0.4258***	–0.1902**	–0.1541*	–0.3746***	–0.4393***	–0.1979**
	(–2.63)	(–2.26)	(–3.76)	(–2.44)	(–1.77)	(–3.03)	(–3.33)	(–2.18)
GDPP^2	0.0133***	0.01300**	0.0220***	0.0127***	0.0099**	0.0168***	0.0227***	0.0135***
	(3.05)	(2.02)	(3.65)	(2.90)	(2.17)	(2.94)	(3.37)	(2.67)
ESTR	–0.0086	–0.0157	–0.0210**	–0.0630***	–0.0091	0.0024	–0.0308**	–0.0686***
	(–1.03)	(–1.01)	(–2.05)	(–3.13)	(–1.10)	(0.20)	(–2.48)	(–3.68)
PRO	–0.0164[a]	–0.0536***	–0.0465***	–0.0731***	–0.0228**	–0.0594***	–0.0367***	–0.0766***
	(–1.45)	(–3.71)	(–5.75)	(–6.63)	(–1.98)	(–4.75)	(–3.71)	(–7.96)
STR	–0.0005***	0.0008**	0.0006***	–0.0003	–0.0005***	0.0004*	0.0006***	–0.0002
	(–2.81)	(2.36)	(3.88)	(–1.04)	(–2.59)	(1.80)	(2.92)	(–0.69)
TIME	–0.0040***	0.0038	–0.0008	–0.0072***	–0.0042***	0.0030	–0.0013	–0.0084***
	(–4.31)	(1.09)	(–0.37)	(–6.12)	(–4.60)	(0.86)	(–0.53)	(–6.29)
Constant term	8.8637***	–5.8480	3.6795	15.163***	9.0995***	–3.8231	4.9274	17.688***
	(4.62)	(–0.90)	(0.87)	(5.87)	(4.77)	(–0.59)	(1.01)	(6.10)
Wald/*F* test	3608.11	8587.89	97879.49	268212.60	3254.96	9450.35	112265.97	175095.23
Sargan test			27.5993	26.3809			25.1717	26.0668
			(1.0000)	(1.0000)			(1.0000)	(1.0000)
AR(1)			–2.0729	–2.0692			–2.0141	–2.0763
			(0.0382)	(0.0385)			(0.0440)	(0.0379)
AR(2)			–1.5559	–1.6422			–1.5736	–1.636
			(0.1197)	(0.1005)			(0.1156)	(0.1018)
Inflection point					3.5667	2.3594	3.2344	3.5938
Obs	360	360	330	360	360	360	330	360

a, *,** and ***: 15%, 10%, 5% and 1% significance level respectively. The values in brackets are *t* values and *z* values. The values in brackets of the Sargan test value, AR(1) and AR(2) are corresponding *P* values.

efficiency on a time sequence. The efficiency values of the previous period are positively correlated with the current period, which also shows that the improvement of the energy efficiency is a continuous and cumulative adjustment process.

For the environmental regulation variables that we focused on, the estimated results of dynamic panel model are basically in accordance with the static panel model. Models 7 and 8 show that environmental regulations have promotion effects on China's total factor energy efficiency. Models 11 and 12 also significantly support that the variables have a U-structure nonlinear relation. The inflection point of the dynamic panel model is slightly higher than that of static panel estimation result. The estimation of the control variables also provides good robustness to the results. The energy consumption structure and the industrial property rights structure pass the 1% significance test.

Why does China's environmental regulation and the total factor energy efficiency present a U-structure? We believe that there are obvious dependency relations between energy efficiency and environment pollution. Different environmental regulation intensities have different influence mechanisms on energy efficiency. When the government enacts weak environmental regulation intensity that does not constitute stress on enterprises in the market, enterprises always spend money on controlling pollution discharges for reasons of short-term profit consideration. The anti-pollution extra spending mainly appears to follow a cost effect. When the environmental regulation intensity increases to the level of the inflection point, the pollution control reversed transmission mechanism gradually forms. The pollution control cost increases further because of treating the end of the pollution discharge, not only reducing the enterprise's profit but also increasing its emission reduction pressure. Therefore, to maintain a competitive advantage in the market, enterprises, on the one hand, must reduce emissions pollution, and on the other, reduce the production cost. Energy, as the main source of pollution, makes enterprises spend more money on improving the technology of energy conservation and emissions reduction. Improving the energy use technology and the methods and structure can not only achieve the requirement of environmental regulation but also increase the energy efficiency. Furthermore, strong environmental regulation establishes certain market barriers to the market entry and hinders the regional industrial transfer. High energy-consuming and high polluting industries must increase investment in technology updates; otherwise, they will be phased out, or transferred to provinces with weaker environmental regulation intensity. Thus, stronger environmental regulation intensity provinces have high energy efficiency, whereas the weaker environmental regulation intensity provinces tend to decline in energy efficiency. The effect of environmental regulation not only depends on the degree of environmental regulation intensity but also on the regulation modes. When the regulation modes are unreasonable, although society and government focus more on energy and pollution problems, the efforts may be wasted and the ideal effect cannot be achieved.

Conclusions

The external diseconomy of environment pollution hastened the birth of environmental regulation. If these regulation measures are aimed at controlling pollution, they would force the increase in China's energy efficiency, thereby reducing the energy stress caused by the rapid expansion of China's economy. Appropriate environmental regulation would likely realize a win-win result of energy conservation and emission reduction. Based on the possibility of this theory, this article analysed the panel data of 30 provinces in China from 2000 to 2012 utilizing the super-efficiency DEA model. The main results are as follows. (i) Holistic energy efficiency of China is relatively low and very imbalanced among different areas. Areas having higher energy efficiency focus are concentrated in the east China, while those with lower focus are in the west. (ii) In general, environmental regulation can promote the increase in energy efficiency by forced mechanism; there is a type of U-shaped relation between the strength of environmental regulation and the total factor energy efficiency, which implies that the weak environmental regulation goes against the increase in energy efficiency; however, it can promote the increase in energy efficiency when the strength of environmental regulation moves through the inflection point. (iii) There is a type of U-shaped relation between the economic development level and the total factor energy efficiency. In addition, enhancing the industrialization level, benefits the energy efficiency, whereas the consumption of coal and state-owned property rights are both negative for energy efficiency. (iv) The differences in U-shaped relationship of developed area and underdeveloped area can help in analysing the plight that exists in the development phase of emerging market countries, and this also offers some policy suggestions. For example, due to the different phase of U-shaped relationship of different areas, each area needs to formulate different environmental regulation policy according to its own physical truth, and strengthen the pertinence of energy consumption and efficiency while formulating environmental regulation policy; it should stimulate the enterprises to reduce energy consumption and to manage energy, thereby promoting harmonious development of environment and energy consumption.

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ACKNOWLEDGEMENTS. We thank the reviewers for their constructive comments and suggestions. We also thank the National Social Science Foundation of China (Grant No. 14ZDA088), the Social Science Foundation of Beijing (Grant No. 14JGA014) and the Ministry of Education Humanities and Social Sciences Research Program (Grant No. 15YJA790020).

Received 4 November 2015; revised accepted 13 January 2016

doi: 10.18520/cs/v110/i10/1958-1968