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The elasticity of the potential of emission reduction to energy saving: Definition, measurement, and evidence from China

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ABSTRACT

Based on energy and CO_2 emission efficiencies, this paper proposes a definition of the elasticity of the potential of emission reduction to energy saving (E_{peres}), and measures the elasticity in China's 30 provincial regions. Although E_{peres} is a relative definition, it can be used (1) to measure the amount of reduced CO_2 emissions per unit fossil energy saving, (2) to reflect the effectiveness of fossil energy saving for CO_2 emission reduction in different regions, and (3) to provide decision-making criteria for selecting pathways for emission reductions in different regions. The results show that compared with energy saving, emission reduction is a more serious issue in China. This indicates that energy saving policies have been highly effective since their implementation during the 11th "Five-Year Plan". With respect to provincial disparities, the emission reductions caused by fossil energy saving are not significant in Beijing, Shanghai, and Guangdong. Fujian province has significant E_{peres}, indicating that emission reduction causing by fossil energy saving is effective. E_{peres} has been increasing over time in Hunan and Hubei. Hainan's E_{peres} has remained less than 1, indicating that its emission-reduction effect of fossil energy saving is worse than in other provinces. Moreover, the elasticity of Eastern China is greater than that of Central China and Western China. This finding sheds light on pathway selection for energy saving and emission reduction in China: it would be more appropriate to encourage fossil energy saving in Eastern China, and to promote clean energy use (e.g., water electricity and solar energy) in Central China and Western China.

1. Introduction

Energy saving and emission reduction have been vigorously measured by the Chinese government (Yang et al., 2017; Zhang et al., 2017). The energy intensity and CO_2 emission intensity of China are expected to be reduced by 16% and 17%, respectively, in 2015 (the end of the 12th "Five-Year Plan" (FYP)) compared with their 2010 levels (the end of the 11th FYP), respectively. In addition, CO_2 emission intensity must be reduced by 40–45% in 2020 (the end of the 13th FYP) compared with their 2005 levels (the end of the 10th FYP). There is a close relationship between the decreases in energy intensity and CO_2 emission intensity (Shao et al., 2016a, 2016b). Zeng and Chen (2016) and Zeng et al. (2016) suggested that an efficient allocation ratio for the carbon emission allowance can help realize energy conservation and emissions reduction goals in China. Similarly, Wang et al. (2011) suggested that reducing carbon emissions requires optimizing energy mix and cutting down energy intensity.

To reduce CO_2 emission intensity, Jiang et al. (2016) also emphasized the importance of building a comprehensive allocation mechanism associated with the carbon quota and increasing the initial proportion of free allocation. Generally, CO_2 emissions can be reduced through fossil energy saving and fuel-mix adjustments. While many studies have focused on energy and CO_2 emission efficiencies (e.g., Fan et al., 2015; Shao et al., 2016c), few papers discuss the correlation between fossil energy saving and CO_2 emission reduction. This paper focuses on the reduction of CO_2 emissions resulting from per unit fossil energy saving (we call it the elastic-

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ity of emission reduction to energy saving, E_{peres}). We empirically estimate the elasticity by using provincial-level data of China, and further analyze the selection of pathways for emission reductions in different regions of China.

In microeconomics, traditional elasticity takes the forms of supply price elasticity, demand price elasticity, demand income elasticity, and the cross-elasticity of demand. Some studies also apply the elasticity in the fields of energy and environmental economics. As a crucial production factor, energy is frequently used in different kinds of elasticities. Based on the application of energy-related elasticity in different cases, the related studies can be classified into several aspects.

First, elasticities have been applied in the general energy field, including a multi-stage energy replacement system (Lowe, 2003), European countries' Armington elasticity (Welsch, 2008), price elasticity concerning Japanese willingness to pay for energy efficiency labels (Galarraga et al., 2011), Mozambique's domestic energy demand (Arthur et al., 2012), income elasticity and price elasticity on industrial energy demand in the Organization for Economic Cooperation and Development (OECD) countries (Adeyemi and Hunt, 2014), and the cross-elasticity of Beijing's energy consumption behavior (He et al., 2014).

Second, elasticities have been applied in the electricity power field, including a short term and long term evaluation of the U.S. residential electricity demand (Silk and Joutz, 1997); the investigation of price elasticities in Pakistan (Jamil and Ahmad, 2011), China (He et al., 2011), South Africa (Inglesi-Lotz, 2011), Western Australia (Fan and Hyndman, 2011), Switzerland (Filippini, 2011), U.S. (Pielow et al., 2012), and Japan (Okajima and Okajima, 2013; and the estimation of the demand elasticity of the electricity market (Yan and Folly, 2014).

Third, elasticities have been applied in fuel and crude oil product fields, including coal demand elasticity of (Masih and Masih, 1996), demand elasticity of Turkey's imported crude oil (Altinay, 2007), price elasticity of gasoline (Brons et al., 2008), crude oil's imported price and its income elasticity in South Africa (Ziramba, 2010), the gasoline price and its income elasticity in Lebanon (Sita et al., 2012), the U.S.'s petrol price elasticity (Lin and Prince, 2013), and the impact of changes in fuel demand on CO_2 emissions in the Lisbon Metropolitan area (Melo and Ramli, 2014).

Most of these studies have focused on the measure of energy (including fuels and electricity) elasticity and its influencing factors. Only Melo and Ramli (2014) conducted a quantitative method to examine the correlation between energy and CO_2 emissions. They also adopted a scenario analysis to discuss how the goal of emission reduction is achieved through the change of fuel price. Their results show that the goal of emission reduction can be achieved only when economic growth slows down. However, this study only focused at the micro-level and cannot facilitate decision-making at the macro-level. Further, their results depend on a large amount of price information and future data information through a scenario analysis. In contrast to Melo and Ramli (2014), our study proposes and examines the elasticity of the potential of CO_2 emission reduction to energy saving. The elasticity measures the corresponding reduction in CO_2 emissions resulting from per unit energy saving. The larger the elasticity value, the more effective the CO_2 emission reduction from energy saving.

Some scholars have conducted meaningful attempts to model the elasticity of the environmental pollution with respect to economic growth (Zhao et al., 2016, 2017). Tapio (2005) constructed a framework to define and estimate the decoupling between environmental pollution and economic growth, focusing on the relationship among GDP, traffic volumes, and CO_2 emissions in the 15 European Union (EU) countries during 1970–2001. Baležentis and Hougaard (2014) investigated the decoupling of energy use and CO_2 emissions for the Lithuanian agricultural sector. Based on Tapio (2005) and using the log-mean Divisia index (LMDI) method, Zhang et al. (2015) provided an approach to identify the types of the decoupling between the changes in GDP and energy consumption in China. Zhou et al. (2006) constructed the slack-based measure index of environmental performance for 30 OECD countries from 1998 to 2002.

Although Zhou et al. (2006) and Baležentis and Hougaard (2014) focused on the relationship between economic development and environmental pollution using different indices, they did not complete an intertemporal comparison based on the input-output database and neither included an energy conservation potential calculation. To fill such a gap, this study focuses on energy saving and CO_2 emission reduction potentials, as well as the calculation of the elasticity. Based on the value of E_{peres}, we can reasonably select pathways for emission reduction in different regions using scientific and effective decision-making.

The value of E_{peres} can be measured using the Data Envelopment Analysis (DEA) method. This method logically reflects the production relationship between the input variables and the output variables at the macro-level. In addition, the method requires no price information and relaxes data availability limitation. Since Fare et al. (2007) proposed the idea of the Environmental Production Technology (EPT) which considers undesirable outputs, studies on measuring energy and environmental efficiencies have become increasingly popular. Zhou et al. (2008) provided a comprehensive literature review on this method, and Zhou and Wang (2016) further presented a literature review on CO_2 allocation issue based on the DEA method. Because of the strong systematic relationship among energy, economy, and the environment, more researchers are using different innovative DEA models to quantitatively investigate both energy and CO_2 emission efficiencies.

In the related literature, research samples have included: (1) the application of the non-radial DEA model at country and sectoral levels, such as for the energy and environmental efficiencies of 26 OECD countries (Zhou et al., 2007), agricultural and environmental efficiencies of European Union countries (Vlontzos et al., 2014), and the greenhouse gas (GHG) emission environmental performance index (EPI) in Lithuanian economic sectors using the Hicks-Moorsteen index (Baležentis et al., 2016); (2) studies on China's provincial efficiency, such as the calculation of resources and environmental efficiencies in China's 30 provinces using Shannon's entropy method (Bian and Yang, 2010), the estimation of China's regional industrial energy efficiency using fixing non-energy input DEA model (Shi et al., 2010), the measure of the potential of emission reduction and opportunity costs using the SBM model (Choi et al., 2012), and the calculation of energy and environmental efficiencies at China's provincial level using the window DEA method (Wang et al., 2012), multi-directional efficiency analysis (Wang et al., 2013a), and the range-adjusted measure approach (Wang et al., 2013b); (3) the studies on electricity generation and power plant performance, such as the measure of the energy and environmental efficiencies of electricity generation using the non-radial directional distance function for OECD countries (Zhou et al., 2012), Korea (Zhang et al., 2013), and China (Zhang et al., 2014), and the estimation of energy and environmental efficiencies using the slacks-based DEA model for China's thermal power generation (Bi et al., 2014).

Although these previous studies have made great progress with respect to methodology and empirical evidence, they leave some open questions. First, most existing studies estimated energy and CO_2 emission efficiencies based on two separate processes; however, the two kinds of efficiencies are inseparable in real-world conditions. The CO_2 emission efficiency is closely related to energy efficiency. In general, fossil energy saving can result in the reduction of CO_2 emissions. Second, although some recent studies simultaneously estimates energy and environmental efficiencies, the comparison of efficiencies has focused at the regional level (e.g. Hermannsson and McIntyre, 2014), and did not include a correlation analysis of the effect of energy saving on CO_2 emission reduction. To address these open areas, this paper focuses on the conception and application of E_{peres}. This indicator brings the concept of elasticity in traditional economics into the fields of energy and environmental economics. By establishing and calculating the elasticity, the effect of energy saving on emission reduction can be more directly identified. This facilitates the better selections for emission-reduction policies and measures.

The rest of this paper is organized as follows. Section 2 introduces the model, approach, and data sources. Section 3 presents and discusses the estimated results of the elasticity at China's provincial level. Finally, Section 4 draws main conclusions and makes policy recommendations.

2. Methodology and data

In this section, we first describe the Environmental Production Technology, and then establish an estimation model for the potential of energy saving and emission reduction. We also propose an elasticity indicator for the potential of emission reduction to energy saving.

2.1. Environmental production technology (EPT)

Assume there are j ($j = 1, 2, \ldots, N$) provincial regions, and each is a decision unit. Each province uses labor (L), energy (E), and capital (K) as the input variables, and produces GDP (Y) and CO_2 emissions (C) as the desirable and undesirable output variables, respectively. The production technology sets can be shown as:

$$T = \left\{(E, L, K, Y, C) : E, L, K \text{ can produce } Y, C\right\} \tag{1}$$

In addition, the production technology sets should satisfy the assumption of weak disposability and null-jointness. The assumption can be expressed as: (i) If $(E, L, K, Y, C) \in T$ and $0 \le \theta \le 1$, then $\left(E, L, K, \theta Y, \theta C\right) \in T$; and (ii) If $(E, L, K, Y, C) \in T$ and $C = 0$, then $Y = 0$. Assumption (i) represents weak disposability. If there is a reduction in CO_2 emissions, then GDP will also be proportionately reduced. Assumption (ii) reflects the fact that there must be CO_2 emissions when GDP is being produced. For CO_2 emissions to not be produced, GDP must not be generated (null-jointness). Only under the conditions (i) and (ii), the production technology sets T can be defined as the Environmental Production Technology sets T. We will follow the non-parametric DEA method used in Fare et al. (2007) and Zhou et al. (2012), using the constant returns to scale (CRS) DEA to express the Environmental Production Technology sets T as follows:

$$\begin{aligned} T = \{(E, P, K, Y, C) : &\sum_{j=1}^{N} z_j E_j \le E_p \\ &\sum_{j=1}^{N} z_j L_j \le L_p \\ &\sum_{j=1}^{N} z_j K_j \le K_p \\ &\sum_{j=1}^{N} z_j Y_j \ge Y_p \\ &\sum_{j=1}^{N} z_j C_j = C_p \\ &z_j \ge 0, j = 1, 2 \cdots N\} \end{aligned} \tag{2}$$

In Eq. (2), p is the unit that will be evaluated. The variables E_p, L_p, K_p, Y_p, and C_p are fossil energy, labor, capital, GDP, and CO_2 emissions for unit p, respectively. C takes "=" to represent the weak disposability and null-jointness of the undesirable output. The element "=" means (i) i.e. $\left(\theta Y_p, \theta C_p\right) \in T$, if $\left(Y_p, C_p\right) \in T$, then $0 \le \theta \le 1$, a proportional reduction of GDP and CO_2 is feasible. It is costly in terms of GDP to decrease CO_2 emissions, and (ii) i.e. $\left(\theta Y_p, \theta C_p\right) \in T$, if $C_p = 0$, then $Y_p = 0$. If there is no CO_2 emissions, no GDP would be produced (null-jointness).

2.2. Estimation model for energy and CO_2 emission efficiencies

We first introduce an estimation model that can simultaneously consider energy and CO_2 emission efficiencies. In the process of production, each DMU tries to minimize input variables (L, K, E), and at the same time, maximize the desirable output Y and minimize the undesirable output C. In China, fossil energy makes up of most energy consumption. In the process of using fossil energy, CO_2 emissions and other undesirable outputs are generated. By calculating of energy and CO_2 emission efficiencies, we could aim to save energy and reduce the undesirable output as CO_2 emissions. Considering the relationship between energy saving and its impact on CO_2 emission reduction, Wang et al. (2012) combined the methods of Bian and Yang (2010) and Shi et al. (2010), and proposed the following model to simultaneously measure energy and CO_2 emission efficiencies:

$$\begin{aligned} &\text{Min}\,\theta + \phi \\ &\sum_{j=1}^{N} z_j E_j + S_p^{e-} = \theta E_p \\ &\sum_{j=1}^{N} z_j L_j + S_p^{p-} = L_p \\ &\sum_{j=1}^{N} z_j K_j + S_p^{k-} = K_p \\ &\sum_{j=1}^{N} z_j Y_j - S_p^{y+} = Y_p \\ &\sum_{j=1}^{N} z_j C_j = \phi C_p \\ &z_j, S_p^{e-}, S_p^{l-}, S_p^{k-}, S_p^{y+} \ge 0, \text{j} = 1, \cdots, \text{N} \end{aligned} \tag{3}$$

Eq. (3) projects an observation onto the efficient boundary of the production possibility set by simultaneously adjusting the quantities of energy use and CO_2 emissions. There is a causal relationship between fossil energy consumption and CO_2 emissions; this paper investigates the elasticity of the potential of emission reduction to energy saving. From the definition and computational perspective, we must focus on the amounts of CO_2 emission reduction from the synchronous fossil energy saving, to satisfy the "simultaneous" characteristic of elasticity definition.

In Eq. (3), θ is the energy efficiency, ϕ is the CO_2 emission efficiency, $S_p^{e-}, S_p^{l-}, S_p^{k-}, S_p^{y+}$ are the slack variables of energy, labor, capital, and GDP, respectively. All other variables have the same definitions as those in Eq. (2). Based on Eq. (3), we can calculate the reduction coefficients of energy input and CO_2 emissions by minimizing energy input and CO_2 emissions when all other variables remain constant. This setting is more consistent with the reality of production processes. The meaning of the target variable is to simultaneously achieve energy saving and minimize CO_2 emissions, even though the two may not be reduced by the same proportion.

2.3. Definition of E_{peres}

The concept of elasticity, which originated from physics and material science, is usually defined as the response of defined variables to external shocks. When there is an inter-dependency between two variables, the growth rate of variable y divided by the growth rate of variable x is defined as the elasticity. In such a function relationship, the variable x is the independent variable, and the variable y is the dependent variable. At the end of the 19th century, the British economist Marshall (2012) proposed the concept of elasticity. Generally, if a continuous functional relationship $y=f(x)$ exists between the independent variable x and the dependent variable y, the elasticity of y to x is called the point elasticity as follows:

$$E_{x,y} = \lim_{\Delta x \to 0} \frac{\frac{\Delta y}{y}}{\frac{\Delta x}{x}} = \frac{dy}{dx} \cdot \frac{x}{y} \quad (4)$$

If a discrete functional relationship exists between the independent variable x and the dependent variable y, the elasticity of y to x is called arc elasticity as follows:

$$E_{x,y} = \frac{\frac{\Delta y}{y}}{\frac{\Delta x}{x}} \quad (5)$$

As Eqs. (4) and (5) show, when variable x changes, the change rate of variable y can be characterized as elasticity. In economics, many specific issues can be considered by applying elasticity. The closer the inter-dependent relationship is, the stronger the elasticity between the two variables is, and vice versa.

As noted above, the correlation between two variables can be largely reflected by their elasticity. In the analytical framework of the Environmental Production Technology, energy is a macro-level input variable, closely related to CO_2 emissions (the undesirable output). The increase of fossil energy can lead to the increase of CO_2 emissions, and vice versa. However, such a qualitative analysis cannot measure the potential effect of the reduction in fossil energy on emission reduction. This requires an elasticity estimate.

To obtain the elasticity, we first build a quantitative relationship between the possible reduction of fossil energy and the potential of emission reduction. Then, we can estimate the degree of difference between the two variables. After that, we can measure the sensitivity degree of emission reduction to fossil energy saving.

The variables E_p and C_p are actual energy and CO_2 emissions in p province, respectively. By solving Eq. (3), θE_p and ϕC_p can be obtained as the theoretical minimized values of the above variables. Using the two theoretical values, we can calculate the theoretical reduced amount of energy $\left(1-\theta\right)E_p$ (energy saving) and the theoretical reduced amount of CO_2 emissions $(1-\phi)C_p$ (the potential of emission reduction). The elasticity relationship between the two reduced amounts can be defined as E_{peres}, expressed in Eq. (6) as follows:

$$E_{peres} = \frac{\frac{\Delta C}{C_p}}{\frac{\Delta E_p}{E_p}} = \frac{\frac{(1-\phi)C_p}{C_p}}{\frac{(1-\theta)E_p}{E_p}} = \frac{1-\phi}{1-\theta} \quad (6)$$

Solving Eq. (3) can only calculate the theoretical minimized values of energy and CO_2 emissions; as such, the elasticity is the arc elasticity. As Eq. (3) shows, there is not necessarily a relationship between the data of energy saving and emission reduction at the macro-level in a certain region. Since the elasticity in a certain region is more related to the reduction coefficients of energy input and CO_2 emissions in that region, the elasticity is a relative definition. This relationship depends on (i) the input- and output-mix in a certain region, which defines the position of a corresponding observation with respect to the technology frontier (surface), and (ii) the shape of the technology frontier, which is determined by the input- and output-mix for the best-practice observations. In other words, DEA measures and the elasticity indicator are all relative ones.

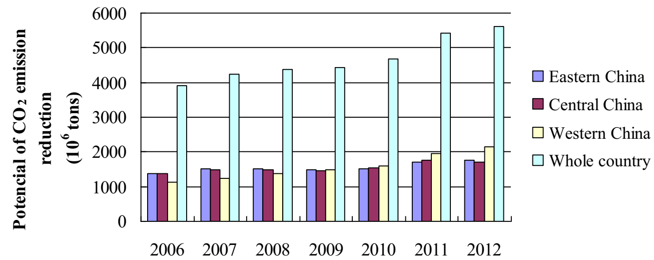

Fig. 1. Trends of the potential of CO_2 emission reduction during 2006–2012.

Intuitively, no reduction in emissions should be possible without reducing fossil energy use. However, in case aggregate measures are used in the relative setting of DEA, the model given by Eq. (3) captures both technical and “allocative” efficiencies. These correspond to energy efficiency (i.e. the inverse of energy intensity) and fuel-mix effects, respectively. Specifically, the changes in fuel consumption might render changes in CO_2 emission in different directions, as different fuel-mixes might govern the emissions for the best-practice frontier. If a certain observation is located on a facet of the technology frontier (surface), a reduction in fossil fuel consumption may remove a slack in the consumption of the specific input with no change in emissions. Such cases should not be common given the actual trends in energy use. Sueyoshi and Goto (2011) summarized the possibilities for the movement towards the production frontier in the energy input-undesirable output space. In case of slack based measures, the two extreme cases can occur: (i) reduction in undesirable output (CO_2 emissions) with the unchanged energy consumption (i.e., the movement along line AK in Fig. 1 in Sueyoshi and Goto (2011)), and (ii) reduction in energy use with the unchanged undesirable output (CO_2 emissions) (i.e., the movement along line CK in Fig. 1 in Sueyoshi and Goto (2011)). It is noteworthy that savings in energy and/or emissions are relative to the empirical frontier.[1] In our setting, Case (i) corresponds to $0<\theta<\phi=1$, while Case (ii) is associated with $0<\phi<\theta=1$. In both cases, we face the circumstances described as “corporate effort” or “managerial effort” (as opposed to “natural reduction”) by Sueyoshi and Goto (2011). Based on the possible combinations of the two reduction coefficients, Table 1 lists the possible values of E_{peres} along with corresponding economic meanings.

The possible values of E_{peres} provide the critical indicators on different effects of energy saving on emission reduction. This allows the transformation from quantitative analysis to qualitative one when defining the relationship between energy saving and emission reduction. The elasticity values of 1 and 0 have particularly significant meaning. For example, in the regions where E_{peres} is greater than 1, the reduction in fossil energy use could cause relatively higher reduction in CO_2 emission, and thus the policy on fossil energy saving appears particularly appealing in such high-elasticity regions.

[1] As an anonymous reviewer pointed out, the elasticity indicator presented in this paper is highly dependent on both energy mix and relative measures. Indeed, these properties apply to all the efficiency measures based on relative frontiers and aggregate data. As the same energy-mix is associated with the same emission intensity, the energy input would not contribute to the emission inefficiency in case that energy input is perfectly decomposed into different kinds of energy with distinctive emission factors under CRS technology. However, this study, as it is the usual practice in existing literature, applies the aggregate quantity of energy consumption as an input variable. Considering the relative nature of the efficiency measures (and the resulting elasticity measure), one can note that the reductions in energy or emissions might be feasible in case that new technologies are adopted.

Table 1
Economic interpretation of the elasticity measure.

Value	Reason	Economic meaning
$E_{peres} > 1$	$0 < \phi < \theta < 1$	The relative extent of reduction in emissions is higher than that in fossil energy use (for a given technology)
$E_{peres} = 1$	$0 < \phi = \theta < 1$	The relative extent of reduction in emissions equals that in fossil energy use (for a given technology)
$0 < E_{peres} < 1$	$0 < \theta < \phi < 1$	The relative extent of reduction in emissions is lower than that in fossil energy use (for a given technology)
$E_{peres} = 0$	$0 < \theta < \phi = 1$	Reduction in fossil energy use yields no emission reduction for a given technology (i.e. fuel-mix effect offsets energy efficiency effect)
Does not exist	$0 < \phi < \theta = 1$	Emission can be reduced without scaling energy use (i.e. fuel-mix effect offsets energy efficiency effect)

In contrast, in the regions where the potential elasticity of emission reduction to energy saving is less than 1, the reduction of fossil energy may not cause significant emission reductions. As such, policies that promote clean energy use should be adopted in these low-elasticity regions. Also, if a certain province has no potential for energy saving (it lies on the frontier with $\theta = 1$), then the value of elasticity does not exist. However, energy saving and emission reduction measures can still be implemented in those regions, as our estimated results of energy and CO_2 emission efficiencies are relative ones as they are rendered by comparison of regions and empirical frontier.

In addition, the value of elasticity is dynamic. By estimating the elasticity for the same province at different stages (horizontal comparison), and estimating the elasticity in the same period for different provinces (vertical comparison), E_{peres} can be comparatively analyzed. This analysis can significantly inform the study of energy and CO_2 emission efficiencies and the dynamic formulation of energy saving and emission reduction policies.

2.4. Data

As introduced above, fossil energy, labor, and capital are the input variables; gross domestic product (GDP) is the desirable output variable; and CO_2 emission level is the undesirable output. The Chinese government established the obligatory target of reducing energy intensity in the 11th FYP for the first time; given this, we choose provincial data during 2006–2012 as our research sample. Due to the absence of energy data in the Tibet autonomous region, our sample includes 30 provincial regions in mainland China. The data are derived from the *China Statistical Yearbook* and *China Energy Statistical Yearbook*. The amount of CO_2 emissions is estimated based on the different kinds of fossil energy consumption and IPCC's (2006) reference method and emission parameters. Capital stock is calculated following Shan's (2008) perpetual inventory method. Capital stock and GDP are measured at 2000 constant prices. Energy consumption data cover all sectors, including production and household sectors, with the unit of tons of coal equivalent (tce). Table 2 shows the summary statistics for the input and output variables in even years.

In general, mainland China can be classified into three regions based on their geographical location and the level of economic development. As Table 3 shows, Eastern China includes 11 provincial regions (8 provinces and 3 municipalities). The total amounts of fossil energy and CO_2 emissions in Eastern China account for more than 40% of the country. Central China includes 8 provincial regions (8 provinces), and the total amounts of fossil energy and CO_2 emissions in this region account for more than 25% of the country. Western China includes 6 provinces, 4 autonomous regions, and 1 municipality, and the total amounts of fossil energy and CO_2 emissions in this region have grown faster than the other two regions. At the end of 2012, the total amounts of fossil energy and CO_2 emissions in Western China exceeded those in Central China.

3. Empirical results and discussion

3.1. Estimation of energy and CO_2 emission efficiencies

Based on the DEA model above, we use Matlab software to obtain the values of θ and ϕ in Eq. (3) as well as the energy and CO_2 emission efficiencies of China's 30 provincial regions. Table 4 shows the values of θ and ϕ in 2012. The results indicate that Beijing, Shanghai, and Guangdong have higher energy and CO_2 emission efficiencies ($\theta = \phi = 1$) than other provincial regions. This means that the three regions are on the DEA frontier, and they do not have additional potential for energy saving and emission reduction compared with other regions. However, since the DEA calculation measures the relative technology efficiency among DMUs, the three regions still have the potential of energy saving and emission reduction, even though the relative space of energy saving and emission reduction is smaller than other regions. In Eastern China, some other provinces also have higher energy and CO_2 emission efficiencies, such as Fujian, Zhejiang, and Jiangsu.

The regions with lower energy and CO_2 emission efficiencies include Ningxia, Shanxi, Inner Mongolia, and Xinjiang (θ and ϕ are less than 0.20). Theoretically, these regions have greater potential for energy saving and emission reduction than other regions. For example, Inner Mongolia has the largest CO_2 emission reduction potential, at 633.25 million tons. However, because they are far away from the DEA frontier, the possibility of reaching the frontier through fossil energy saving is slight. Therefore, more effective policies and measures for energy saving and emission reduction in these regions should be considered. In Western China, provinces such as Guizhou, Qinghai, and Gansu also have lower energy and CO_2 emission efficiencies.

The energy and CO_2 emission efficiencies in the provinces of Eastern China are higher than those in other provinces. Even Hebei ($\theta = 0.38$, $\phi = 0.33$) and Hainan ($\theta = 0.37$, $\phi = 0.39$), which have the lowest efficiencies among the provinces of Eastern China, have higher energy and CO_2 emission efficiencies than Shanxi ($\theta = 0.13$, $\phi = 0.11$) and Ningxia ($\theta = 0.08$, $\phi = 0.07$). These two provinces have the lowest efficiencies among the provinces of Central China and Western China, respectively. In addition, ϕ values of most inefficient DMUs are lower than θ values, indicating that the potential for emission reduction is larger than the potential for energy saving. Compared with energy saving, the pressure of emission reduction is more rigorous. Yunnan, Jiangxi, and Henan experienced a larger difference between the values of ϕ and θ than other regions. The three provinces are in Central China and Western China, and their energy and CO_2 emission efficiencies are at the middle level among all the provinces. This indicates there are larger potentials for energy saving and emission reduction in these three provinces. The Hainan province is the only province where the value of ϕ (0.39) is greater than the value of θ (0.37); this is noteworthy because it implies that the pressure of energy saving is greater than the pressure of emission reduction. This result can be attributed to Hainan's specific energy structure. There is low production and consumption of coal in Hainan province, leading to lower CO_2 emissions generated by fossil energy (57.27 million tons, ranking the 29th among 30 provinces).

Table 2
Descriptive statistics for inputs and outputs.

Variable	Year	Maximum	Minimum	Mean	Standard deviation
Energy consumption (10^4 tce)	2006	26,556.36	884.67	8710.72	6070.74
	2008	31,633.42	1400.95	10,064.46	7040.12
	2010	35,279.24	1405.99	11,676.63	7784.70
	2012	38,592.06	2069.12	13,330.41	8737.56
Population (10^4 persons)	2006	9392.00	548.00	4295.57	2630.51
	2008	9544.00	554.30	4351.33	2648.94
	2010	10,430.31	562.67	4432.58	2707.25
	2012	10,594.00	573.17	4482.70	2721.45
Capital stock (billion RMB in 2000 constant price)	2006	46,060.06	2645.97	17,263.73	11,765.25
	2008	60,461.99	3330.20	22,738.10	15,250.83
	2010	82733.01	4533.88	31,201.21	20,332.63
	2012	108,804.10	6298.21	41,509.03	26,377.70
GDP (billion RMB in 2000 constant price)	2006	20,721.07	504.71	6423.25	5192.22
	2008	26,284.60	640.47	8255.76	6656.93
	2010	32,409.50	813.44	10427.37	8280.67
	2012	38,557.93	1016.72	12,857.27	9934.03
CO_2 emissions (10^4 t)	2006	69,614.39	1883.82	22,806.05	16,115.49
	2008	82,803.76	3432.95	26,330.10	18,682.52
	2010	91,837.42	3418.08	30,409.76	20,560.21
	2012	10,0090.50	4990.57	34,681.05	23,133.99

Table 3
Statistics on China's regional energy consumption and CO_2 emissions.

Region	Province	Year	Energy consumption (10^4 tce)	CO_2 emissions (10^4 t)
Eastern China	Beijing (BJ), Tianjin (TJ), Hebei (HB), Liaoning (LN), Shanghai (SH), Jiangsu (JS), Zhejiang (ZJ), Fujian (FJ), Shandong (SD), Guangdong (GD), and Hainan (HAN)	2006	121,815.24	314,346.31
		2008	139,905.49	359,849.95
		2010	161,163.77	411,348.66
		2012	178,272.14	453,570.43
Central China	Shanxi (SHX), Jilin (JL), Heilongjiang (HLJ), Anhui (AH), Jiangxi (JX), Henan (HEN), Hubei (HUB), and Hunan (HUN)	2006	77,634.25	208,189.42
		2008	87,505.65	234,910.24
		2010	98,783.54	264,632.80
		2012	109,153.18	291,709.07
Western China	Inner Mongolia (IN-MON), Guangxi (GX), Chongqing (CQ), Sichuan (SC), Guizhou (GZ), Yunnan (YN), Shaanxi (SH'X), Gansu (GS), Qinghai (QH), Ningxia (NX), and Xinjiang (XJ)	2006	61,872.23	161,645.87
		2008	74,522.78	195,142.72
		2010	90,351.50	236,311.44
		2012	112,487.08	295,151.95
Whole country	30 provinces	2006	261,321.72	684,181.61
		2008	301,933.92	789,902.91
		2010	350,298.81	912,292.90
		2012	399,912.40	1,040,431.45

Regarding efficiency results, this study is similar to finding from Bian and Yang (2010) and Choi et al. (2012). In Bian and Yang's (2010) study, the efficiency of Beijing, Shanghai, Guangdong is 1, the mean value of the efficiency of Eastern China is higher than Western China. Ningxia, Qinghai, and Guizhou were ranked lowest. In Choi et al.'s (2012) study, the mean value of the efficiency of Eastern China is higher than Western China. Ningxia, Qinghai, and Shanxi were ranks lowest. However, Wang et al. (2013b) reached different conclusions: (1) The efficiencies of Hainan and Sichuan are equal to 1 in 2010; (2) Liaoning, Hebei, Shanxi, and Inner Mongolia were ranked lowest; and (3) the mean value of the efficiency of Western China is higher than that of Eastern China.

Based on these results, we can further estimate the theoretical potential of emission reduction in various regions during 2006–2012. Fig. 1 shows the estimated results. In 2006, the potentials of emission reduction in Eastern China, Central China, and Western China were 1389.48, 1379.31, and 1137.8 million tons, respectively. This indicates that the potentials for emission reduction in Eastern China and Central China were very close and higher than the potential for Western China. However, during 2006–2012, the growth rates of the potentials of CO_2 emission reduction in Eastern China and Central China were both stable; the growth rates in Western China were faster. By the end of 2012, the potential of emission reduction in Western China was significantly higher than those in Eastern China and Central China. The potential of emission reduction in Western China as a proportion of the whole country increased from 29.13% in 2006 to 38.13% in 2012. From the perspectives of both CO_2 emission efficiency and the potential of CO_2 emission reduction, Western China has the greatest pressure for CO_2 emission reduction among the three regions.

3.2. Estimation of E_{peres}

To conduct a targeted analysis on the pathway of CO_2 emission reduction in each province, we apply Eq. (6) to calculate E_{peres} for each province. Table 5 shows the results. The values of the elasticity in most provincial regions can be obtained, with the following exceptions: Beijing (2010–2012), Shanghai (2006–2012), Fujian (2008), and Guangdong (2006–2012). These provinces do not have the elasticity values compared with other provincial regions, because the potentials for energy saving and emission reduction in these regions are equal to 0. This indicates that these regions are located on the frontier in the achievement of energy saving and emission reduction.

Based on mean elasticity, Fujian is ranked as the highest province. The elasticity values of most regions are more than 1, that

Table 4
Values of θ and ϕ in China's 30 provinces in 2012.

Region	Province	Energy consumption (10^4 tce)	θ	Energy-saving potential (10^4 tce)	CO_2 emissions (10^4 tons)	ϕ	Emission reducing potential (10^4 tce)
Eastern	SH	8087.90	1.00	0.00	19,435.36	1.00	0.00
Eastern	GD	20,590.29	1.00	0.00	51,171.25	1.00	0.00
Eastern	BJ	4382.84	1.00	0.00	9787.31	1.00	0.00
Eastern	FJ	8137.41	0.97	255.04	20,949.54	0.91	1943.37
Eastern	ZJ	14,810.59	0.81	2766.34	37,792.29	0.77	8856.55
Eastern	JS	25,546.66	0.75	6449.68	66,295.87	0.70	20,001.95
Eastern	TJ	6424.32	0.72	1830.86	15,900.94	0.69	4921.25
Eastern	SD	38,592.06	0.47	20328.78	100,090.55	0.44	56,519.86
Eastern	LN	23,862.81	0.41	13,970.14	58,801.99	0.41	34,796.78
Eastern	HB	25,210.88	0.38	15,634.82	67,618.45	0.33	45,018.76
Eastern	HAN	2626.39	0.37	1659.12	5726.87	0.39	3503.11
Central	HUN	10,204.39	0.76	2465.78	27,097.05	0.70	8180.18
Central	JX	5718.24	0.69	1762.80	15,201.12	0.61	5951.14
Central	HUB	13,028.59	0.69	4066.22	34,724.72	0.63	12,698.88
Central	AH	11,436.22	0.55	5107.37	30,855.01	0.50	15,416.09
Central	HEN	20,454.98	0.50	10,209.31	54,523.30	0.43	31,036.55
Central	HLJ	13,518.18	0.46	7283.40	34,935.85	0.44	19,560.09
Central	JL	9615.51	0.41	5696.41	25,365.25	0.35	16,613.52
Central	SHX	25,177.07	0.13	21869.27	69,006.78	0.11	61,620.13
Western	SC	11,017.18	0.79	2326.49	27,849.04	0.76	6762.22
Western	CQ	5765.56	0.64	2053.27	14,,871.98	0.59	6135.11
Western	GX	7335.30	0.57	3159.04	18,919.54	0.49	9593.54
Western	YN	7093.07	0.49	3639.48	19,534.03	0.39	11,818.35
Western	QH	2069.12	0.27	1510.81	4990.57	0.25	3743.80
Western	GS	7160.16	0.25	5338.70	18,117.82	0.23	13,900.41
Western	SH'X	15,384.78	0.25	11,586.29	39,522.25	0.21	31,039.85
Western	GZ	9590.15	0.20	7629.66	26,419.16	0.17	22,041.20
Western	XJ	13,654.54	0.17	11,333.64	33,916.56	0.15	28,733.77
Western	IN-MON	26,785.25	0.17	22,288.54	73,366.66	0.14	63,325.05
Western	NX	6631.97	0.08	6115.02	17,644.34	0.07	16,489.93
Total		399,912.40	–	198,336.28	1,040,431.45	–	560,221.46

Table 5
Elasticity values and ranks of thirty provinces in China over 2006–2012.

Province	2006	2007	2008	2009	2010	2011	2012	Mean	Rank
FJ	2.07	3.39	–	8.63	6.40	2.07	2.96	4.25	1
GX	1.17	1.18	1.28	1.52	1.34	1.19	1.18	1.27	2
JX	1.06	1.08	1.08	1.18	1.20	1.23	1.27	1.16	3
HUN	1.06	1.07	1.09	1.18	1.20	1.21	1.25	1.15	4
JS	1.06	1.07	1.03	1.18	1.21	1.19	1.20	1.13	5
ZJ	1.06	1.06	1.08	1.14	1.14	1.18	1.25	1.13	6
HUB	1.06	1.07	1.09	1.17	1.14	1.15	1.17	1.12	7
YN	1.04	1.05	1.06	1.08	1.10	1.15	1.18	1.09	8
AH	1.05	1.06	1.06	1.08	1.10	1.11	1.12	1.08	9
CQ	1.02	1.03	1.03	1.08	1.09	1.13	1.16	1.07	10
HEN	1.03	1.04	1.04	1.07	1.06	1.10	1.14	1.07	11
SC	1.00	1.01	1.02	1.06	1.05	1.11	1.15	1.06	12
JL	1.01	1.02	1.02	1.05	1.08	1.08	1.11	1.05	13
HEB	1.03	1.03	1.03	1.05	1.07	1.07	1.07	1.05	14
TJ	1.03	1.02	1.05	1.10	1.02	1.05	1.09	1.05	15
SD	1.02	1.03	1.00	1.05	1.04	1.07	1.07	1.04	16
GZ	1.01	1.02	1.02	1.03	1.03	1.05	1.05	1.03	17
IN-MON	1.02	1.02	1.02	1.02	1.04	1.03	1.04	1.03	18
HLJ	1.00	1.01	1.01	1.03	1.02	1.04	1.04	1.02	19
SH'X	1.00	1.00	1.00	1.01	1.03	1.04	1.04	1.02	20
SHX	1.01	1.01	1.01	1.02	1.02	1.03	1.03	1.02	21
NX	1.01	1.01	1.01	1.01	1.01	1.01	1.01	1.01	22
GS	0.99	1.00	1.00	1.01	1.01	1.02	1.03	1.01	23
LN	0.99	0.99	0.99	1.01	1.01	1.01	1.01	1.00	24
XJ	0.98	0.98	0.99	1.00	1.01	1.02	1.02	1.00	25
QH	0.97	0.98	0.99	1.00	0.98	1.02	1.03	1.00	26
HAN	0.68	0.91	0.91	0.91	0.89	0.95	0.97	0.89	27
BJ	0.83	0.78	0.68	0.60	–	–	–	0.72	28
SH	–	–	–	–	–	–	–	–	–
GD	–	–	–	–	–	–	–	–	–

Note: "-" denotes that the value of E_{peres} does not exist.

means CO_2 emission reduction effect is significant if fossil energy use is reduced in these regions. Only the elasticity values of Liaoning, Xinjiang, and Qinghai are equal to 1. The elasticity values of Hainan and Beijing are less than 1, indicating that the effect of fossil energy saving on CO_2 emission reduction is not obvious and these provinces should construct other pathways into low-carbon development.

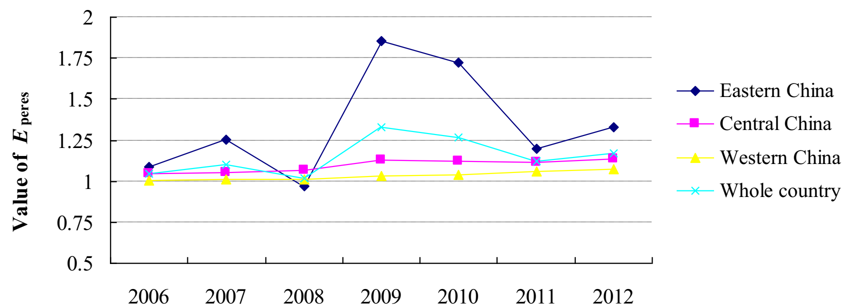

Fig. 2. Trends of E_{peres} values in different regions in China over 2006–2012.

The elasticities are well-defined for most of provinces, indicating that fossil energy saving can induce an emission reduction effect in these provinces. The elasticities of Beijing (2006–2009) and Hainan (2006–2012) are less than 1, indicating that fossil energy saving does not results in a significant effect of emission reduction. This is because Beijing has a higher level of urbanization, and electricity plays a dominant role in its total energy consumption. In contrast, the low-carbon industrial structure and energy structure in Hainan results in its lower fossil energy consumption. The elasticities of Hebei, Shanxi, Inner Mongolia, Liaoning, Heilongjiang, Shaanxi, Gansu, Qinghai, Ningxia, and Xinjiang remain approximately 1 during 2006–2012, indicating that fossil energy saving can lead to the close effect of CO_2 emission reduction in these provinces. Hebei and Liaoning, industrial provinces in Eastern China, have CO_2 emission reduction potentials of 450.19 and 347.97 million tons, respectively.

The other provinces mentioned above are in Central China and Western China. The common characteristic of these provinces is that their energy efficiencies are very close to their CO_2 emission efficiencies. Both efficiencies remain at a low level, at less than 0.5. In addition, Beijing's elasticity value experienced a declining trend during 2006–2009, indicating that the effect of fossil energy saving on emission reduction had been declining. Fujian's elasticity value was far greater than 1, and even reached 8.63 in 2009. This implies that fossil energy saving could have a significant effect on emission reduction.

As Fig. 2 shows, the elasticity of Eastern China was ranked the highest; the exception was in 2008 when its elasticity value (0.97) was lower than values in Central China and Western China (1.07 and 1.01, respectively). The average elasticity value in Eastern China during 2006–2012 was 1.34; in 2009, the elasticity value of Eastern China (1.85) was significantly greater than those of Central China (1.13) and Western China (1.02). The annual average elasticity value in Central China was 1.10 and was consistently been higher than in Western China (1.03). Therefore, we find that the effect of fossil energy saving on emission reduction in Eastern China is greater than the effects in Central China and Western China. The annual average value of E_{peres} across the country was 1.15 during 2006–2012. This indicates that China should continue to reduce fossil energy use to achieve emission-reduction goals.

3.3. Pathway selection of emission reduction

Based on the results of the potential and elasticity of emission reduction, a correlation analysis was conducted to identify the targeted pathway for regional emission reductions. Fig. 3 places the E_{peres} in each province in 2012 along the x-axis, and the potential for emission reduction in each province in 2012 along the y-axis.

As Fig. 3 shows that 26 provincial regions are mainly located in the upper left area, the lower left area, and the lower right area. The upper left area includes provinces with larger potential for emission reductions and a smaller elasticity, including Inner Mongolia,

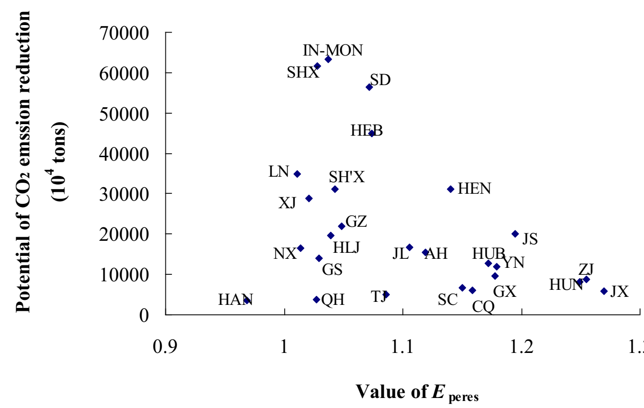

Fig. 3. Elasticity and the potential of emission reduction in China's provinces in 2012.

Shanxi, Shandong, Hebei, and Liaoning. In these provincial regions, clean energy should be used to replace fossil energy. The "clean use" of high-carbon energy and energy efficiency improvements can be encouraged in these regions. For example, Inner Mongolia could promote the use of wind and solar power to generate electricity and connect the grid within this region to reduce emissions. Because Shanxi province has abundant coal resources, this province could promote the application of the clean technology of "coal to gas". Shandong, Hebei, and Liaoning are traditional industrial provinces, with a high level of industrialization and heavy dependence on fossil energy consumption. These regions should eliminate underdeveloped production capacity and to improve energy efficiency through technology advances and upgrades.

The provincial regions in the lower left area have some potential for emission reduction and small elasticity; these regions include Hainan, Qinghai, Gansu, Ningxia, and Xinjiang. The local governments of these regions should maximize the potential for clean energy use, such as biomass, wind and solar power. From the perspective of household' energy use, these regions should be encouraged to use electricity to reduce fossil energy consumption. From the perspective of industrial energy use, energy efficiency should be effectively improved.

The provincial regions in the lower right area have some opportunity for emission reduction and a large elasticity; these regions include Jiangxi, Zhejiang, Hunan, Jiangsu, and Hubei. Because these provinces have a higher level of industrialization and urbanization, their pathways for emission reduction should be to save fossil energy, speed up technological transformation, and implement compulsory actions. This would eliminate the under-developed production capacity with great energy consumption and CO_2 emissions. In addition, some provinces in this area (e.g., Hubei and Chongqing) have established a platform pilot for CO_2 emission trading. This indicates that it is feasible to adopt market mechanism to abate the CO_2 emissions of energy-intensive enterprises.

4. Conclusions and policy implications

Using Environmental Production Technology as the basic analytical framework, this paper proposes a definition of E_{peres}, measures the elasticity in China's provincial regions, summarizes the trends and regional characteristics of the elasticity, and suggests the differentiated pathways of energy saving and emission reduction in different regions. The results indicate that energy efficiency is generally better than CO_2 emission efficiency at China's provincial level. This means that implementing the obligatory target of reducing energy intensity in China's 11th FYP was effective. Beijing, Shanghai, and Guangdong are at the forefront in both energy and CO_2 emission efficiencies. Eastern China is better than Central China and Western China in both energy and CO_2 emission efficiencies. The emission-reduction potential of Western China has been increasing over the past several years, and has overtaken the potential of Eastern China and Central China.

In addition, E_{peres} exists in most provincial regions of China. A few provincial regions with better performances of energy saving and emission reduction, including Beijing, Shanghai, Guangdong, and Fujian, do not have elasticity values in some years. This is because compared with other provincial regions, the potentials for energy saving and emission reduction in these regions are equal to 0. The provincial regions with lower energy saving and emission reduction performance, such as Shanxi, Inner Mongolia, Guizhou, Ningxia, and Xinjiang, have a smaller elasticity. The elasticity in Eastern China is consistently higher than those in Central China and Western China; Western China has the smallest elasticity. China's annual average elasticity was 1.15 during the period of 2006–2012, indicating that reducing CO_2 emissions through fossil energy saving is effective. For those regions with a small elasticity, cleaner energy should be used to replace fossil energy. For those regions with a large elasticity, the efficiency of fossil energy use should be improved.

The findings of this study, and the general situation associated with energy saving and CO_2 emission reduction in China, leads to the following policy recommendations.

First, the Chinese government should intensify differentiated regional energy saving and emission reduction policies. Our results show that CO_2 emission reduction effects resulting from fossil energy saving have clear regional disparities (different elasticities). As such, to hit the CO_2 emission peak in 2030, the Chinese government should implement more reasonable policies that accommodate regional diversified characteristics.

Second, the co-management between energy and the environment should be strengthened. The increase of CO_2 emissions is closely related to the increase of the total fossil energy consumption. Fossil energy consumption and CO_2 emissions have been rigid constraints on China's current economic development. This paper proposes, defines and classifies E_{peres} to provide a co-analysis of CO_2 emission reduction and fossil energy saving. Our results show that the whole country's elasticity is more than 1; this indicates that the Chinese government should conduct co-management, by taking fossil energy consumption as the source and CO_2 emissions as the target. Provinces with higher elasticity values should implement powerful measures to achieve low-carbon goals, by reducing the use of coal.

Third, this paper highlights the choices associated with differentiated pathways of CO_2 emission reduction. The Chinese government should consider real-world situations in different regions and raise differentiated emission reduction targets for different regions. The motivation for proposing E_{peres} is to measure the actual effect of energy saving on emission reduction. Our results suggest that Western China should popularize renewable energy to reduce CO_2 emissions because of relative lower elasticity. In contrast, Eastern China should further reduce fossil energy consumption. Different provincial regions should choose suitable pathways to achieve energy saving and emission reduction based on their industrial structure, energy endowment, and economic development level. This will lead to a "win-win" state of economic development and CO_2 emission reduction.

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