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Dilemma between economic development and energy conservation: Energy rebound effect in China☆

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ABSTRACT

Promoting technological development to improve energy efficiency has been the primary method of energy conservation in China. However, the existence of energy rebound effect will impose negative effects on the final result of energy saving. In this article, we adopt the Malmquist index approach to estimate the contribution of technological progress to economic growth. We also employ Logarithmic mean weight Divisia index (LMDI) to measure the impact of technological improvement on the energy intensity. Based on the above, we set up a model to estimate the technology-based energy rebound effect in China. The results show that, over 1981–2009, energy rebound effect amounts averagely to 53.2%, implying that China cannot simply rely on technical means to reduce energy consumption and emission. Economic instruments should also be applied as supplements to ensure results of energy conservation and emission reduction.

1. Introduction

China's primary energy consumption and carbon dioxide (CO_2) emission has shown a growing trend since 1981. In 2009, China's energy consumption was 3066.5 million tons of coal equivalent (Mtce) [11], in which electricity consumption was 3681 terawatt hour [48] and its carbon emission reached 7518.5 Mt [10]. Energy saving and emission reduction has been playing increasingly important role in China's economic growth, as the country has to cope with greenhouse gas (GHG) emission reduction as well as face strong energy and environmental constraints. The State Council of China issued a "Comprehensive Program of Energy Conservation and Emission Reduction during 12th Five-Year" in 2010. According to the program, energy intensity, measured as the ratio of total energy consumed in standard coal equivalent to real gross domestic product (GDP) in China, should be cut down by 16% in 2015 from the 2010 level. Also, its carbon intensity, measured as the ratio of total CO_2 emission to GDP will go down by 17%. This just reveals the Chinese government's strong determination on energy saving and emission reduction.

Like in several countries, the Chinese government also treats it as a primary method of energy conservation to improve energy efficiency by promoting technological progress. Some achievements have been made. Energy intensity in China declined from 1.66 tce/1000USD in 1980 to 0.39 tce/1000USD in 2009 (at 2005 prices) [37]. However, the question one may ask is this: is it really feasible to reduce energy consumption by improving energy efficiency? The energy rebound effect tells us that technological progress not only improves energy efficiency, but also promotes economic growth therefore raising the demand for energy. This energy increment can partially offset the energy saved by energy efficiency improvement. Therefore, economic development actually has a negative impact on energy saving [19] and instead of reducing energy consumption technological progress will increase energy demand [46]. For a developing country like China, sustaining rapid economy growth is the primary mission. Thus, it is a dilemma for the Chinese government to implement energy conservation and emission reduction while simultaneously maintaining economic growth. Lin and Jiang [17] estimated China's energy demand, and their result implies that China's high energy

Abbreviations: LMDI, logarithmic mean weight Divisia index; tce, ton of coal equivalent; Mt, million tons; Mtce, million tons of coal equivalent; GDP, gross domestic product; GHG, greenhouse gas; CO_2, carbon dioxide; DEA, data envelopment analysis; CRS, constant returns to scale; VRS, variable returns to scale; IRS, increasing returns to scale; DRS, decreasing returns to scale.

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demand will continue in the future when facing the rapid economic development. Lin and Liu's results showed that in 2020, China's CO_2 emissions will reach about 9400 Mt and suggested energy conservation as the effective way to the low-carbon society [38].

In this regard, cutting down the size of energy rebound effect is the key to address the dilemma and the useful way of maintaining sustainable energy development [44]. The size of energy rebound at macro-economic level can tell us how much economic growth will offset energy savings. In designing strategies for energy conservation and emission reduction such rebound effects have to be accounted for [45]. This result has important reference value for policy making, and this is why we choose this topic in the paper.

The second part reviews the researches on energy rebound effect. In the third part, we estimate the contribution of technological progress to economic growth, and decompose the energy intensity indicators; then, we build up an estimation model for calculating the energy rebound effect. In the fourth part, we describe the data used and calculate the energy rebound effect at macro-economic level in China. In the last part, we provide the main conclusions and relevant recommendations for policy making.

2. Theoretical background

The idea of energy rebound effect dates back to 1866, when Jevons [15] in his book "The Coal Question"[1] proposed that "It is wholly a confusion of ideas to suppose that the economical use of fuel is equivalent to a diminished consumption. The very contrary is the truth." For the first time, it called into doubt the energy efficiency's positive effect on energy conservation in the economic circles.

The first to study rebound effect phenomenon in the form of economics literature was by Brookes and Khazzoom. Brookes [8] focused on rebound effect at the macroeconomic level and believed that energy efficiency can promote economic growth. If the impact of economic growth is large enough, the direct result of improving energy efficiency is more energy consumption. And Brookes [9] summarized research progress on energy rebound effect, including historical experience, theoretical foundation and empirical support. Khazzoom [40] pointed out that energy efficiency will usually reduce the marginal cost of energy service. If the demand for energy services is sufficiently sensitive to changes in its cost, the actual reduction of energy consumption and reduction of energy consumed by per unit of energy services are not in proportion to change. Brookes and Khazzoom according to their own studies, proposed a hypothesis: improved energy efficiency will release funds to promote further economic growth, thus greatly accelerating the depletion of energy resource. This is the famous Khazzoom–Brookes hypothesis. According to Greening et al. [13], energy rebound effect increases energy consumption by three paths. First, direct rebound effect: the improvement of energy efficiency cut down the effective utility cost of energy, which will increase energy consumption. This mechanism should include two aspects, the substitution effect and the income effect. The substitution effect means energy with decreased effective costs will substitute other production factors, such as capital and labor. As for income effect, the decreasing effective cost of energy raises the real income therefore further increasing the demand for energy. Second, the indirect rebound effect: the decreasing effective utility costs of energy can lower the price of those energy-consuming products; then in the economic system, the demand for these products will be increased therefore increasing the energy demand. Third, rebound effect of the overall economic system: it means that improvement of energy efficiency can raise the overall demand for energy. The decrease in effective costs of energy can reduce the prices of intermediate and final products. In this regard, it leads to system adjustment of prices in the overall economy, which may narrow the cost gap between production costs of energy-intensive products and those of less energy-intensive products, so the economy will further increase the demand for energy. Unfortunately, these studies above mentioned only used a theoretical basis for discussing the possibility of energy rebound effect's existence, lacking empirical evidence.

Saunders for the first time made use of empirical methods to measure the size of the energy rebound effect and made conclusions that energy efficiency improvement could promote economic growth and the substitution between energy and other factors also can affect the size of energy rebound effect. Saunders [21], for the first time, employed Cobb–Douglas and CES production function to estimate energy consumption with 1.2% annual increase in energy efficiency. From a macroeconomic perspective, Saunders confirmed the possibility of the existence of rebound effect. Saunders [22] employed Howarth's Cobb–Douglas production function, "balanced growth's" Cobb–Douglas function, and Howarth's Leontief formulation to calculate the multitude of energy rebound effect. He also compared good qualities and shortcomings between these different functions. Saunders [23] adopted eight types of production and cost functions for exploring how energy efficiency gains affect energy consumption. Saunders' studies are mainly under the neo-classical growth theory framework and systematically sum up the influence of different function form on the size of rebound effect in the empirical studies. Saunders' research gives sufficient theoretical proof for the existence of energy rebound effect and has attracted more attention on the rebound effect, thus triggering a series of controversies.

In recent years, empirical research on energy rebound effect developed rapidly and achieved fruitful results. Most of these researchers are advocates of energy rebound. Kelly [34] calculated the magnitude and significance of explanatory variables on residential energy consumption. He found that in the multivariate case, dwelling efficiency explained very little of the variance of residential energy consumption and dwelling efficiency was shown to have a negative effect on energy consumption.

Madlener and Alcott [19] summarized some of the discussions around the rebound effect .They attempted various approaches for answering the question of whether total energy consumption less or greater due to energy efficiency increases. At the microeconomic level, they thought that analyzing prices, substitution and income effects would be a useful way of investigating direct rebound effect. At the macroeconomic aspect, they focused on the changes in energy efficiency in the aggregate non-monetarily. More importantly, Madlener and Alcott believed that energy efficiency improvements put great impact on the marginal consumer who cannot afford energy services before energy efficiency improvements. This also largely validated the important role of price changes on the rebound effect and provided direction for future empirical research.

More empirical studies to measure the rebound effect by estimating the price elasticity or efficiency elasticity have been carried out. These empirical studies have adopted various econometric methods and sample data. Energy rebound effect of different levels (for example, at national, regional, or household levels) is estimated [24,6,16]. Calculation models include the static models that provide single estimation of the elasticity, and dynamic models that provide both short-term and long-term estimation of elasticity [24,41]. Many function forms such as linear function, logarithmic function, dual logarithmic functions, and translog functions have been

[1] Jevons, W.S. (1866). "The Coal Question", quoted from Ref. [5].

adopted [24,5,34]. Estimation methods that are commonly adopted include least squares, generalized least squares, instrumental variable method, two-stage least squares, three-stage least squares, fixed effect models, random effect models, the error correction models and maximum likelihood methods; correspondingly, sample selected includes time-series data, cross-sectional data, panel data, and so on [6,24,42,43]. In addition, with the development of Computable General Equilibrium (CGE) model, several studies use CGE model to measure the energy rebound effect [1,27,28]. CGE has good explanatory power and takes into account the factors that have significant impacts on economic system. However, due to the complexity of CGE model and its difficulty in data collecting, it has not yet been widely used in estimating energy rebound effect.

Accompanied with the development of some new concept, for example low-carbon economy and green economy, some researchers from low-carbon and green economy point to study the rebound effect. Herring [35] presented the views of economists, as well as green critics of 'the gospel of efficiency'. He acknowledged that some of the savings from efficiency improvements will be taken in the form of higher energy consumption—so called 'take-back' or rebound effect. He argued that a more effective CO_2 emission reduction policy is to concentrate on shifting to non-fossil fuels, like renewable, subsidized through a carbon tax. He further exerts that limiting energy consumption would require energy conservation rather than energy efficiency. Although there is intense dispute over magnitude of energy rebound, Herring is one of advocates of energy rebound. Alfredsson [36] explores the quantitative effect on energy use and carbon dioxide (CO_2) emissions if house-holds were to adopt 'green' consumption patterns. His results show that under the behavioral and technological changes into "green" patterns, on average 14% of the initial savings in energy requirements were taken back by the substitution effect. From these studies, it can be seen that as the concept of low-carbon economy CO_2 emission reduction has been included into the rebound effect. Rebound effect has a new conceptual development.

Apparently, since developed countries' energy markets are relatively mature, it is a mainstream method to estimate the energy rebound effect by estimating the energy price elasticity. But in China's undeveloped energy markets, price does not truly reflect the supply and demand situation. Hence the method mentioned above is not feasible. In addition, studies in developed countries can easily get access to detailed data of many specific sectors, such as transportation sector, manufacturing industry, and consumers. But in China, the data of some specific departments are not available, leading to great difficulties in calculating energy rebound effect of specific sectors. Therefore, there are few empirical researches on energy rebound effect of specific sectors in China. OuYang [20] estimated residential energy rebound effect in China, and reached the conclusion that the residential energy rebound effect should be between 30% and 50%. However, his result has no support from Chinese data, and he conducted the analysis mainly through summarizing the results of studies on other developing countries.

The first empirical research on energy rebound effect in China was carried out in 2007. As energy price elasticity method is not applicable, Zhou and Lin [33] first established a model and adopted the ridge regression approach to estimate total factor productivity so as to calculate the energy rebound effect in China. The results illustrated that since 1978, China's energy rebound effect fluctuated between 30% and 80%. Liu and Liu [18] estimated energy rebound effect of each Chinese province based on provincial panel data, and they found that during the period over 1986–2005, rebound effect of Chinese western regions topped, followed by that of Central China and then Eastern China. Wang and Zhou [26] estimated the energy rebound effect of China by using an improved model. Guo et al. [14] measured energy rebound effect of China's industrial sector and got the result that energy rebound effect was 46.38% over 1979–2007. It can be seen that the basic model in these empirical studies of China's energy rebound effect is uniform; the only difference is econometrical method to estimate parameters.

3. Methodology

3.1. Basic energy rebound effect calculation model

Energy intensity is often regarded as an important indicator measuring energy efficiency [29]. Energy efficiency improvement means that the energy consumption for producing the same rate of GDP decreases. In this regard, improving energy efficiency means energy conservation. Thus, except for coal, oil, natural gas and nuclear, the energy efficiency is regarded as "the fifth-largest energy" [7]. Many countries are trying to improve energy efficiency by encouraging technological innovation so as to achieve the purpose of energy saving. However, this idea for energy saving is challenged by the rebound effect. Energy rebound effect implies that advances in technology are often followed by economic growth, which leads to growth in energy consumption. This part of energy consumption growth will partially or even wholly offset the energy saved by energy efficiency improvement. This is the theoretical basis for Zhou and Lin's model which calculates the technology-based energy rebound in China at macro-economic level [33]. We treat this model as the basic energy rebound effect calculation model. The model is shown as:

$$R_t = \frac{A_t^*(Y_{t+1} - Y_t)^* I_{t+1}}{Y_{t+1}^*(I_t - I_{t+1})} \quad (1)$$

where t denotes time; I_t is energy intensity at period t, representing energy efficiency; Y_t denotes aggregate output at period t; A_t denotes total factor Productivity at period t; R_t represents energy rebound effect at period t.

In equation (1), $Y_{t+1}{}^* (I_t - I_{t+1})$ denotes energy saving due to energy efficiency improvement. $A_t{}^* (Y_{t+1} - Y_t)$ denotes economic growth caused by technological progress. Then energy consumption increment can be denoted as $A_t{}^* (Y_{t+1} - Y_t){}^* I_t$. According to equation (1), the energy rebound effect is actually the ratio of energy consumption increment brought about by economic growth in total energy saving resulted from energy efficiency improvement. Both the energy efficiency improvement and economic growth here are caused by technological progress.

3.2. Modified energy rebound effect calculation model

As China's energy market is undeveloped, we cannot estimate China's energy rebound effect by estimating energy price elasticity like those studies on developed countries. The model described in Equation (1) is an alternative method, which is a proper method for estimating energy rebound effect at macro-economic level in China. This model, however, has two weaknesses. We improve the model as follows.

3.2.1. Improvement in energy efficiency index

In Equation (1), $Y_{t+1}{}^* (I_t - I_{t+1})$ represents energy saving resulted from energy efficiency improvement. Unfortunately, this formula cannot accurately represent the energy efficiency improvement from technological progress, because $Y_{t+1}{}^* (I_t - I_{t+1})$ also contains scale changes that also can lead to changes in energy efficiency. For example, economic structural changes can improve energy efficiency. In this article, we will adopt LMDI (Logarithmic mean weight Divisia index) decomposition method to decompose the variation of energy intensity and identify the contribution of technological advances to energy efficiency improvement.

$$\Delta I = \Delta I_e + \Delta I_y \tag{2}$$

ΔI_e represents changes in energy intensity caused by technological progress; ΔI_y represents changes in energy intensity caused by variation of structural effect.

Then, we can obtain the parameter δ that denotes the impacts of technological improvement on energy intensity:

$$\delta = \Delta I_e / \Delta I \tag{3}$$

3.2.1.1. Calculation of energy intensity index: an LMDI approach.- There are two approaches which are commonly used for energy intensity decomposition namely: the structural decomposition method based on input–output framework and factorization method based on depolymerization. Factorization method is a method that decomposes the overall changes into variation of several main factors. Laspeyres decomposition method and Divisia decomposition method are two main factorization methods widely adopted in recent studies. Ang [2–4] made the comparison between Laspeyres decomposition method and Divisia decomposition method in terms of theoretical foundation, adaptability, practicality, and accessibility of result interpretation. His results showed that the performance of LMDI is more preferred in terms of the above four aspects. In addition, LMDI method can decompose all factors without residual, and it can also be applied to the decomposition of incomplete data set. Therefore, we select LMDI for the decomposition of energy intensity.

Energy intensity can be decomposed as:

$$I = \frac{E}{\mathrm{GDP}} = \frac{\sum_i E_i}{\sum_i \mathrm{GDP}_i} = \sum_i \frac{E_i}{\mathrm{GDP}_i} * \frac{\mathrm{GDP}_i}{\sum \mathrm{GDP}_i} = \sum_i e_i * y_i \tag{4}$$

where i denotes industry type, i = 1, 2, 3; e_i represents energy intensity of industry i, manifesting the technical effect; y_i represents the proportion of added value of industry i in GDP, revealing the structural effect.

Based on equation (4), we can adopt the LMDI method to decompose the changes in energy intensity as:

$$\begin{aligned} \Delta I = \Delta I_e + \Delta I_y &= \sum_i L(W_{it}, W_{i,t-1}) \ln(e_{it}/e_{i,t-1}) \\ &+ \sum_i L(W_{it}, W_{i,t-1}) \ln\left(y_{it}/y_{i,t-1}\right) \end{aligned} \tag{5}$$

ΔI_e represents changes in energy intensity caused by technical effect; ΔI_y denotes changes in energy intensity due to structural effect.

$L(W_{it}, W_{it-1})$ is called logarithmic average weight.

$$L(W_{it}, W_{i,t-1}) = (W_{it} - W_{i,t-1}) / (\ln W_{it} - \ln W_{i,t-1});$$
$$W_i = e_i * y_i$$

From equation (5), we can further get the technical effect parameter of energy intensity changes, denoted by δ:

$$\delta = \Delta I_e / \Delta I$$

3.2.2. Improvement in total factor productivity

Currently, Solomon remainder method is widely used to calculate the total factor productivity, which measures the contribution of technological progress to economic growth [33,26,18]. When the overall production function is estimated, Solomon remainder method calculates the total factor productivity through deducting weighted value of input factors' growth rates from GDP growth rate. The estimate of total factor productivity has been a conundrum in economics circles. The advantage of Solomon remainder method lies in its operational simplicity, but it has actually two shortcomings. First, when applying Solomon remainder method in the calculation of total factor productivity, it is necessary to make strict assumptions on the economic behaviors and industrial organization which make it far from reality. More importantly, Solomon remainder method proposes that the total factor productivity only represents the contribution of technological advances to economy growth while ignoring the impacts of efficiency changes on economy growth. In this regard, the total factor productivity cannot be further decomposed by the Solomon remainder method, under which the contribution of technological progress to economy growth cannot be well denoted.

Malmquist index approach can make up the two shortcomings above. First, Malmquist index approach does not require such strict behavioral assumptions as needed in Solomon remainder method and its calculation principle lies only on the optimization of the production. Moreover, Malmquist index approach decomposes the total factor productivity into two parts, the one resulted from the technical progress and the one resulted from the efficiency variation. In this regard, Malmquist index can help us identify the part of economic growth resulted from technological advances. Therefore, we choose the Malmquist index method to calculate the total factor productivity, from which we can obtain the contribution of technological advances to economic growth, which is denoted by α.

3.2.2.1. Total factor productivity growth: a Malmquist index approach. Malmquist index method is used to measure productivity changes of production decision-making units during the given period. Malmquist index method, as a method for calculating the total factor productivity, has been mature and widely used in empirical studies. Yan and Wang [30] adopted the Malmquist index approach to estimate the total factor productivity in China over 1978–2001, and then further decomposed the total factor productivity into technological progress index and efficiency change index. Zheng [32]adopted the Malmquist index method and estimated the total factor productivity of overall China over 1979–2001. Sun and Liu [25] considered the constraint of carbon intensity target allocated by the Chinese government and also adopted the same method to estimate the total factor productivity of provinces in China over 2000–2007.

In this article, we treat each year during 1981–2009 as a decision-making unit. Then we adopt the output-oriented Data Envelopment Analysis (output-oriented DEA model) proposed by Färe et al. to calculate the Malmquist index (namely the total factor productivity) [12]. Further, by comparing the production of each year with the production frontier, we decompose the total factor productivity of each year into technological progress index and efficiency change index.

Suppose we have n production decision-making units, that is, $\mathrm{DMU}_j(x_i,y_i)$ (j = 1,…,n). Where x_i denotes input of DMU, i = 1, 2…m; y_i denotes output of DMU, i = 1, 2… q; $x_i > 0$, $y_i > 0$ ($\forall i$), $x \in R^m$, $y \in R^q$.

We define the production of DMU_j in year t as:

$$\mathrm{DMU}_j t(x_i, y_i) = \mathrm{DMU}_j(x_i^t, y_i^t) = \mathrm{DMU}_j(x_i, y_i)^t$$

According to Färe et al. [12], the Malmquist productivity index M_j can be disaggregated multiplicatively into technological development index and efficiency index:

$$M_j = \mathrm{TECH}_j \times \mathrm{EFFCH}_j$$

$$\mathrm{TECH}_j = \left[\frac{D^t\left(X_j^{t+1}, Y_j^{t+1}\right)}{D^{t+1}\left(X_j^{t+1}, Y_j^{t+1}\right)} \frac{D^t\left(X_j^t, Y_j^t\right)}{D^{t+1}\left(X_j^t, Y_j^t\right)}\right]^{1/2} \quad (6)$$

$$\mathrm{EFFCH}_j = \frac{D^t\left(X_j^{t+1}, Y_j^{t+1}\right)}{D^t\left(X_j^t, Y_j^t\right)} \quad (7)$$

Equation (6) captures the changes in total factor productivity caused by technological progress over period between t and $t+1$, and TECH_j is the technological development index, denoted by α_t;

Equation (7)[2] measures the variation of total factor productivity caused by efficiency change over period between t and $t+1$, and EFFCH_j is the efficiency improvement index.

Based on the two improvements, the modified energy rebound effect calculation model is:

$$R_t = \frac{\alpha_t * (Y_{t+1} - Y_t) * I_{t+1}}{Y_{t+1} * (I_t - I_{t+1}) * \delta_t} \quad (8)$$

The numerator denotes the energy consumption increment caused by economic growth driven by technological progress while the denominator represents energy saving brought about by the energy efficiency improvement.

4. Data and results

4.1. Data

We have collected the data on inputs (including capital investment, labor, and energy inputs) and aggregate outputs (GDP) of China's economy, the three industries' industrial value added and energy consumption, all of which range from 1980 to 2009.

(1) Capital investment: In this article, we employ the physical capital stock to represent capital investment. We adopt the perpetual inventory method used by Ye [31] to estimate the capital stock of China over 1980–2009.[3] The capital stock data are adjusted to the 2000 prices. Data come from "China Statistical Yearbook".
(2) Labor: We adopt the employed population at the yearend as the labor input variable. Data come from "China Statistical Yearbook" and China Premium Database [11].
(3) Energy inputs: We employ China's total primary energy consumption as energy input variable. Different types of energy consumed are converted into standard coal equivalent, which are from "China Energy Statistical Yearbook".
(4) GDP: We adopt the real GDP data at 2000 price level. GDP at current prices and the GDP deflator are from "China Statistical Yearbook".
(5) Energy consumption of the three industries: Industrial energy consumption data over 1994–2009 are from China Premium Database [11]; industrial energy consumption data over 1980–1993 are collected and calculated by author based on energy consumption data of every sector, which are from "China Energy Statistical Yearbook 1980–1993".
(6) Industrial value added: We adopt the real industrial value added at 2000 prices. Real industrial value added data are calculated based on Industrial value added index and Industrial value added at current prices, data of which are from China Premium Database [11].

4.2. Estimation results

Based on the modified model as shown in equation (8), energy rebound effects in China are shown in Fig. 1.

The results show that during the period over 1981–2009 energy rebound effect in China is averagely up to 53.2%. This result is close to the results of Liu and Liu [18], which is 53.7%. From Fig. 1, it can be seen that the result of the basic model in Zhou and Lin's research [33] is higher than the result of this paper in most years. One of the main reasons for this result is that we made improvement on calculating the total factor productivity, by which we excluded the impact of the efficiency changes on economic growth and the rebound effect so as to make the total factor productivity reflect technological advances' effect more accurately. Thus, our result is closer to the reality.

In addition, the result in this paper is higher than results of most studies on developed countries. For example, Small and Dender [24] found that the long-term energy rebound effect in U.S. Department of Transportation was 22.2%; Jin [16] manifested that long-term rebound effect of residential electricity in South Korea was 38%. It is noteworthy that most foreign researches focused mainly on energy rebound effect in specific sectors like household life and transport sectors, rather than on that of the macroeconomic level. Furthermore, Greening et al. [13] reviewed and summarized a number of empirical studies on U.S. energy rebound effect. They found that there was no identical conclusion on the degree of rebound effect. The size of rebound effect varies between the different countries, mainly due to the fact that the cost of energy utility and the expectation for energy demand are different. For China, technological advances are mainly present in the production sector, and the Chinese economy has kept growing fast during the recent years. Both of these two facts may make it understandable that energy rebound effect in China is higher than that in other countries [33].

According to Fig. 1, energy rebound effect generally fluctuates between 30% and 100% except for some extreme cases in certain years. In 1990, 2003, and 2004, the emergence of negative energy rebound effect implies that technological progress did not promote energy conservation, and it actually led to more energy consumption. It is consistent with the results of Zhou and Lin [33]. In 1990, energy rebound effect in China showed a negative value, resulted from the negative impacts of technological progress on economic growth. It also illustrates that structural effect (Zhou and Lin [33] called "soft" technological progress effect) plays an important role in economic growth, as the structural effect pushes the economy forward despite the negative impacts of technological improvement on economic growth. The negative value of energy rebound effects in 2003 and 2004 should be attributed to the rise of energy intensity, which means, energy efficiency was not improved while technical effect of energy intensity was greater than 1, indicating that unreasonable economic restructuring hindered the energy efficiency improvement therefore blocking the energy conservation of the overall economy. The highest value of energy rebound effect emerged in 2005, up to 182.6%. This is because of that, the changes in energy efficiency around 2005 was only 0.0007, while at the same time the economy experienced a relatively higher growth.

[2] The detailed steps to calculate Equations (6) and (7) can be seen in the Färe et al. [12].

[3] The calculation is based on the formula: $K_t = K_{t-1}(1 - \varsigma_t) + I_t$. K_t denotes physical capital stock in year t; ς_t denotes rate of depreciation; I_t denotes investment in year t.

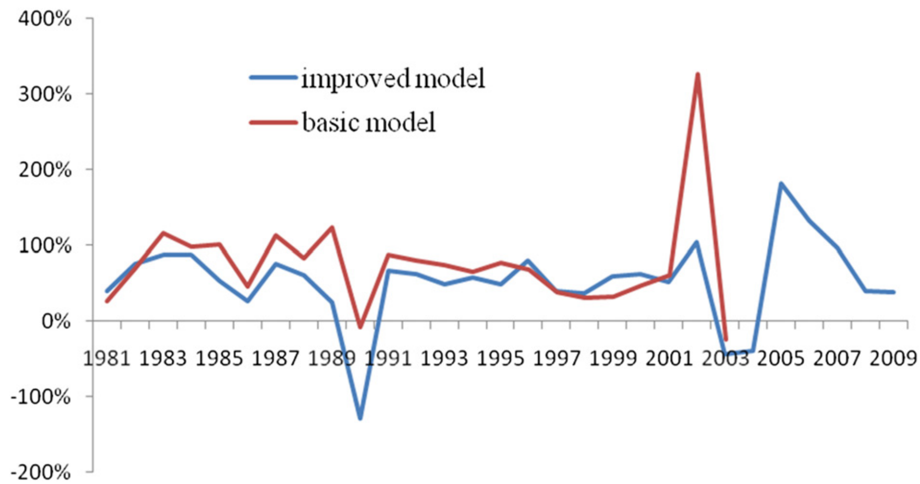

Fig. 1. Energy rebound effect in China.

5. Conclusions and policy suggestions

In this article, we improve the energy rebound effect model and estimate the energy rebound effect in China over the period 1981–2009. Malmquist index method is adopted for estimating total factor productivity, from which we obtain the contribution of technological progresses to economic growth. In addition, LMDI approach is employed to decompose the energy intensity, from which we can obtain the technical effect parameters of energy intensity. The efforts above just make the energy rebound effect calculation model closer to reality and make its estimation more accurate. The results show that over 1981–2009, energy rebound effect does exist in China's national economy system, and energy rebound effect is averagely 53.2%, and some negative cases also exist.

Based on the results from this study, we give the following policy recommendations.

The existence of the energy rebound indicates that energy efficiency improvement does not necessarily result in energy consumption reduction. It implies that stimulating technological progress alone cannot address the dilemma between maintaining economic growth and accomplishing energy conservation and emission reduction targets. It should be supplemented by economic instruments. Currently, the Chinese government policies on energy saving and emission reduction are mainly carried out by administrative measures. After 1998, specific loans for energy-saving infrastructure construction and energy-saving technological transformation have been abolished, and stimulating policies for energy conservation and emission reduction are insufficient. Although administrative measures may be effective in the short run, the existence of the energy rebound effect highlights the importance of market-oriented measures to energy conservation, such as energy pricing reforms, energy resource taxes, carbon taxes, and emissions trading, which are more effective in controlling energy consumption and emissions.

The importance of energy price reform is reflected in the following aspects:

According to energy substitution theory, energy and capital within an economy system or a specific sector are inter-substitutive under certain conditions [39]. Specifically, with energy costs increase, more capital would be put in developing energy-efficient technologies, which would probably reduce energy consumption. However, if energy prices remain unchanged, an increase in energy efficiency cuts the real cost of energy, which will lead to an increase in energy demand. In this regard, the rebound of energy demand just makes the actual energy saving (due to energy efficiency improvement) less than anticipated.

On the contrary, raising energy prices can provide incentives for firms and individuals to undertake energy conservation efforts. The climbing energy prices can raise the energy costs, which just stimulate the enthusiasm in energy saving and emission reduction. For individuals and enterprises, energy saving due to energy efficiency improvement can offset the cost rising caused by energy price rise. When energy efficiency is improved and the overall cost of energy does not decline, the size of energy demand rebound will be relatively small; at the same time, higher energy prices can also constrain the increase in energy demand. Therefore, raising energy prices may be more effective in achieving energy saving and emission reduction.

Currently, the Chinese government sets the energy intensity target for each of the country's provinces. Meanwhile, the Chinese government also tries to maintain low energy prices to support industrial competitiveness and social stability [47]. As a result, the achievement of energy saving through efficiency improvement will be less than expected due to rebound effect. In this regard, the current low energy price policies contradict the energy conservation efforts and add to the difficulty in achieving energy saving and emission reduction targets. Therefore, the energy price reforms in China, namely increasing energy prices to reflect energy scarcity and environmental externalities cost will be crucial for mitigating the energy rebound effect.

In this article, we estimate the size of energy rebound effect at macro-economic level, but the impacts of price variation on energy rebound effects are not revealed, which will be the focus of our future researches.

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