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# EMPIRICAL ANALYSIS OF THE LONG TERM ENERGY REBOUND EFFECT BASED ON THE ENERGY EFFICIENCY ENDOGENOUS MODEL

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## Abstract

Energy efficiency causes long-term energy rebound effect. Based on this mechanism and assumed the energy efficiency to be endogenous, the expression of energy saving and energy rebound effect is gotten from a distribution equation. This equation includes energy efficiency, economic income, capital and energy consumption. In addition, sensitivity analysis of this expression is made. The result shows that: (1) The reverse effect is always existed in the long-time energy efficiency in China. To a large extent, the economic growth in China relies on capital and energy input, so that the increase of energy efficiency causes the increase of energy intensity effect under the action of the capital investment; (2) Reducing the capital intensity effect and energy-capital substitutional effect will be helpful to bring down the energy intensity effect; (3) Reducing production dependence on capital and energy will reduce the energy rebound effect; (4)



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Increasing the elasticity to the labor given by economic income and the elasticity to energy efficiency given by energy usage will reduce the energy rebound effect.

## 1. Introduction

The energy rebound effect is the paradox that the total energy consumption volume increases with the improvement of energy efficiency. It is a heated topic in both China and abroad for the research of energy economy, but the research into this paradox still at the starting point. In terms of the research, the researchers overseas try to define this effect by adopting another concept-energy saving. Saunders [1, 2] defined energy saving by higher energy efficiency to be the elasticity of energy consumption volume against energy efficiency. This definition is accepted by most scholars. In terms of the time of the energy rebound effect, Sorrell et al. [3] thought that it should be divided into 3 phases: the short term effect, the mid-term effect, and the long term effect. In China, only few essays on the research of energy rebound effect can be found. Huang [4] summarized all definitions of energy rebound effect from macroscopic and microscopic perspective. He believes that the definitions of the effect from the macroscopic perspective are unified, and it can be theoretically well analyzed with the production CES function. In terms of the scale of the energy rebound effect, Saunders [1, 2] thought the increase in energy efficiency will not help to reduce energy consumption, but rather adds to it, i.e., it will have a reverse effect. Zhou and Lin [5] and Wang and Zhou [6] used all factor productivities to represent energy efficiency and calculated the energy rebound effect brought about by technology innovation. Their conclusion is that technology innovation will bring down energy consumption by 60%. Zhou and Wang’s definition cannot be used to explain the mechanism of energy rebound effect, but their idea that promoting productivity and reducing energy intensity by technology innovation will lead to energy rebound should be approved.

To sum up, although the existence of energy rebound effect is already widely acknowledged by scholars home and abroad, differences of its definition, mechanism, and scale still exist due to different approaches and targets of researches. The mainstream scholars adopt the definition by Saunders [1] thought the energy rebound effect should be viewed from short term, mid term and long term perspectives.

The definitions of energy rebound effect and energy saving by Saunders [1] are adopted in this essay. First, based upon the perturbation equation of energy efficiency, the arithmetic expression of energy saving and energy rebound effect can be derived. Furthermore, the essay analyzes the energy rebound effect caused by the increase of energy efficiency; second, based on the endogenous theory, the essay analyzes the impact given to the necessary amount of capital and energy input by the changes in energy efficiency, and also analyzes the energy rebound effect under this mode; finally, it analyzes the energy rebound effect of our country from the long term perspective with examples.

## 2. Establishment of the Energy Rebound Effect Model and its Analysis

Saunders [1] defined the energy saving from the increased energy efficiency "$h$" as the rebound "$\eta_h$" of energy consumption volume "$E$" against energy efficiency. Then the energy rebound effect can be expressed as:

$$R_h = 1 + \eta_h.$$

In this arithmetic expression, $\eta_h = \dfrac{\partial \ln E}{\partial \ln h} = \dfrac{h}{E} \times \dfrac{\partial E}{\partial h}$.

Furthermore, Saunders [1] classified the rebound effect as follows: if $R_h > 1$, then the rebound effect is called "*reverse effect*"; if $R_h = 1$, then it is called "*thorough rebound effect*"; if $R_h < 1$, then it is called "*partial rebound effect*"; if $R_h = 0$, then it is called "*null rebound effect*"; and if $R_h < 0$, then it is called "*excessive storage effect*".

In his research of energy rebound effect, Saunders [1] adopted the following production function model:

$$Y = a(hE)^{\sigma_1} K^{\sigma_2} L^{\sigma_3}, \qquad \sigma_1 + \sigma_2 + \sigma_3 = 1. \tag{1}$$

In this function model, $Y$ refers to the economic income, $h$ stands for energy efficiency, $E$, $K$ and $L$, respectively, refer to energy consumption volume, material capital stock and labor. $\sigma_1$, $\sigma_2$, $\sigma_3$ represent the output rebound coefficients of the corresponding factors of production.

Under the assumption of fixed labor and variable exogenous energy efficiency, Saunders [1] proved with partial equilibrium analysis that there exists the reverse effect when the energy efficiency is improved in short term, and he also calculated the short term energy savings by energy efficiency increase, i.e., $\sigma_1/1-\sigma_1$. Based on Saunders' theory, Wei [7] deduced that the long term energy saving from increased energy efficiency is:

$$\eta_h = \frac{h}{E} \times \frac{\partial E}{\partial h} = \frac{h}{Y} \times \frac{\partial Y}{\partial h} = \frac{\sigma_1}{\sigma_3}. \tag{2}$$

Actually, the increase of energy efficiency not only promotes economic growth, it also means the equal amount of economic output consumes less energy, or the same amount of energy will generate more output. From this point of view, the increase in energy efficiency will be helpful in bringing down the energy intensity. As a result, Wei [7] attributed the reverse effect from energy efficiency to the overestimation.

From the long term perspective, the changes in energy efficiency will ultimately give its impact to the factor market, such as capital and labor demand. If the price of the production factors remains unchanged, the changes in energy efficiency will bring fluctuation to energy consumption amount, capital input, and labor demand through the market, and will consequently generate the energy rebound effect.

Assume the returns to scale remain fixed, from equation (1), we can deduce:

$$y = a(hN)^{\sigma_1} k^{\sigma_2}. \tag{3}$$

In this equation, $y = Y/L$, $N = E/L$, $k = K/L$.

If the returns to scale are fixed, but energy efficiency is flexible, with the aid of C-D production function, then we can reduce the 3-dimensional market system, i.e., energy, capital and labor to a 2-dimensional one, i.e., energy and capital, with labor being the reference. The impact to labor from the increased energy efficiency will then be converted into the impact to the energy consumption amount per labor and the capital input per labor. Under this circumstance, the elasticity of labor to energy efficiency will be zero.

According to the definition of energy saving, we can get:

$$\eta_h = \overline{\eta}_h = \eta_h^{\overline{n}} + \eta_h^{y} = (\eta_h^{m} + \eta_h^{v}) + \eta_h^{y}. \tag{4}$$

In this equation, $\overline{n} = N/Y$ stands for energy intensity per labor, $m = E/K$ refers to energy and capital allocation, $v = K/Y$ represents capital intensity, and $\overline{\eta}_h$ is the elasticity of energy consumption amount per labor to energy efficiency.

Equation (4) shows under the influence of capital market and energy market, energy saving $\eta_h$ can be divided into energy intensity effect per labor $\eta_h^{\overline{n}}$, and economic income per labor effect $\eta_h^{y}$. The first one can be subdivided into energy-capital substitutional effect $\eta_h^{m}$, and capital intensity effect $\eta_h^{m}$. The changes in energy efficiency will generate the long term energy rebound effect through energy-capital substitutional effect, capital intensity effect, and economic income per labor effect.

Suppose the production functions to be the fixed returns of scale. Then the first-order condition for the organism of production is

$$y = \frac{P_{EL}}{P} \times \frac{N}{\sigma_1}, \qquad y = \frac{P_{KL}}{P} \times \frac{k}{\sigma_2}. \tag{5}$$

Here, $P_{EL}$ is the relative price of energy and labor, $P_{KL}$ is the relative price of capital and labor, and $P$ is the yield price.

**Model 1.** Suppose the production functions to be the fixed returns of scale while energy efficiency is exogenous variable to analyze the increased energy efficiency's influence over the economic income per labor, energy consumption amount per labor and capital per labor.

From equations (3) and (5), we can get:

$$\begin{cases} F_1 = y - a(hN)^{\sigma_1} k^{\sigma_2}, \\ F_2 = y - \dfrac{P_{EL}}{P} \times \dfrac{N}{\sigma_1}, \\ F_3 = y - \dfrac{P_{KL}}{P} \times \dfrac{k}{\sigma_2}. \end{cases} \tag{6}$$

The Jacobian matrix of equation (6) is:

$$J_h = \begin{pmatrix} \dfrac{\partial F_1}{\partial y} & \dfrac{\partial F_1}{\partial N} & \dfrac{\partial F_1}{\partial k} \\ \dfrac{\partial F_2}{\partial y} & \dfrac{\partial F_2}{\partial N} & \dfrac{\partial F_2}{\partial k} \\ \dfrac{\partial F_3}{\partial y} & \dfrac{\partial F_3}{\partial N} & \dfrac{\partial F_3}{\partial k} \end{pmatrix} = \begin{pmatrix} 1 & -\dfrac{P_E}{P} & -\dfrac{P_{KL}}{P} \\ 1 & -\dfrac{P_E}{P} \times \dfrac{1}{\sigma_1} & 0 \\ 1 & 0 & -\dfrac{P_{KL}}{P} \times \dfrac{1}{\sigma_2} \end{pmatrix}. \tag{7}$$

We can note $\dfrac{\partial F_1}{\partial h} = -\sigma_1 \dfrac{Y}{h}$, $\dfrac{\partial F_2}{\partial h} = 0$, $\dfrac{\partial F_3}{\partial h} = 0$, then the perturbation equation of energy efficiency is:

$$\begin{pmatrix} 1 & -\dfrac{P_E}{P} & -\dfrac{P_{KL}}{P} \\ 1 & -\dfrac{P_E}{P} \times \dfrac{1}{\sigma_1} & 0 \\ 1 & 0 & -\dfrac{P_{KL}}{P} \times \dfrac{1}{\sigma_2} \end{pmatrix} \times \begin{pmatrix} \dfrac{\partial y}{\partial h} \\ \dfrac{\partial N}{\partial h} \\ \dfrac{\partial k}{\partial h} \end{pmatrix} = -\begin{pmatrix} -\sigma_1 \dfrac{Y}{h} \\ 0 \\ 0 \end{pmatrix}. \tag{8}$$

Solve the above equation, and combine it with (5), we can get:

$$\begin{cases} \eta_h^y = \dfrac{h}{y} \dfrac{\partial y}{\partial h} = \dfrac{\sigma_1}{\sigma_3}, \\ \overline{\eta}_h = \dfrac{h}{N} \dfrac{\partial N}{\partial h} = \dfrac{\sigma_1}{\sigma_3}, \\ \eta_h^k = \dfrac{h}{k} \dfrac{\partial k}{\partial h} = \dfrac{\sigma_1}{\sigma_3}. \end{cases} \tag{9}$$

From (9), we can infer:

$$\begin{cases} \eta_h^m = \overline{\eta}_h - \eta_h^k = 0, \\ \eta_h^v = \eta_h^k - \eta_h^y = 0, \\ \overline{\eta}_h^n = \eta_h^m + \eta_h^v = 0. \end{cases} \tag{10}$$

The conclusion drawn from Model 1 is the same as that from Wei [7]. From the long term perspective, if the energy efficiency is exogenous, its increase will only affect the economic income efficiency, and eventually lead to the increase of energy consumption amount, i.e., the reverse effect.

**Model 2.** Suppose the production functions to be the fixed returns of scale while energy efficiency is endogenous variable to analyze the increased energy efficiency's influence over the economic income per labor, energy consumption amount per labor, and capital per labor.

Suppose energy consumption is the necessary condition for capital input, then increase the capital input will lead to more energy consumption, while increase energy efficiency will reduce energy consumption. Then the relation between energy consumption amount, energy efficiency, and capital is:

$$E = uh^{-\gamma_1}K^{\gamma_2}, \qquad \gamma_1 + \gamma_2 = 1. \tag{11}$$

Then the formula of energy efficiency is:

$$\begin{pmatrix} 1 & -\frac{P_E}{P} & -\frac{P_{KL}}{P} \\ 1 & -\frac{P_E}{P} \times \frac{1}{\sigma_1} & 0 \\ 1 & 0 & -\frac{P_{KL}}{P} \times \frac{1}{\sigma_2} \end{pmatrix} \times \begin{pmatrix} \frac{\partial y}{\partial h} \\ \frac{\partial N}{\partial h} \\ \frac{\partial k}{\partial h} \end{pmatrix} = \begin{pmatrix} \sigma_1\gamma_2 \frac{Y}{h} \\ -\gamma_1 \frac{Y}{h} \\ \frac{\gamma_1}{\gamma_2} \frac{Y}{h} \end{pmatrix}. \tag{12}$$

Solve (12) and combine it with (5), we can get

$$\begin{cases} \eta_h^y = \frac{h}{y}\frac{\partial y}{\partial h} = \frac{\sigma_1}{\sigma_3} - \frac{\gamma_1\sigma_2/\gamma_2}{\sigma_3}, \\ \overline{\eta}_h = \frac{h}{N}\frac{\partial N}{\partial h} = \frac{\sigma_1}{\sigma_3} - \gamma_1, \\ \eta_h^k = \frac{h}{k}\frac{\partial k}{\partial h} = \frac{\sigma_1}{\sigma_3} - \frac{(1-\sigma_1)\gamma_1/\gamma_2}{\sigma_3}. \end{cases} \tag{13}$$

From (13), we can get

$$\begin{cases} \eta_h^m = \overline{\eta}_h - \eta_h^k = \dfrac{(1-\sigma_1)\gamma_1/\gamma_2}{\sigma_3} - \gamma_1, \\ \eta_h^v = \eta_h^k - \eta_h^y = -\dfrac{\gamma_1}{\gamma_2}, \\ \overline{\eta}_h^n = \eta_h^m + \eta_h^v = \dfrac{\gamma_1\sigma_2/\gamma_2}{\sigma_3} - \gamma_1. \end{cases} \tag{14}$$

From (13) and (14), we can get different types of energy rebound effects:

(1) When $\dfrac{\sigma_2/\gamma_2}{\sigma_3} > 1,$ then $\eta_h > 0,$ $\overline{R}_h > 1,$ and energy rebound effect is the reverse effect;

(2) When $\dfrac{\sigma_2/\gamma_2}{\sigma_3} = 1,$ then $\eta_h = 0,$ $\overline{R}_h = 1,$ and energy rebound effect is the thorough rebound effect;

(3) When $\dfrac{\sigma_2/\gamma_2}{\sigma_3} < 1,$ then $\eta_h < 0,$ $\overline{R}_h < 1,$ and the energy rebound effect is the partial rebound effect.

The result from Model 2 shows:

(1) The result from Model 2 is smaller than that from Model 1. Under model 2, the increase in energy efficiency directly brings down energy consumption amount and reduces the scale of energy saving.

(2) Compared with Model 1, the main reasons for smaller energy savings in Model 2 are: if $\sigma_2/\gamma_2 > \sigma_3,$ then Model 2 has a stronger energy intensity effect but a weaker economic income effect, compared to Model 1. That the scale of reduction in economic income effect is higher than the scale of increase in energy intensity effect is the main reason for lower energy rebound effect; if $\sigma_2/\gamma_2 = \sigma_3,$ then there is no energy intensity effect in Model 2. Capital input will not affect energy intensity, but will reduce the economic income effect. The reduction in the economic income effect is the main cause for weaker energy rebound effect in Model 2. If $\sigma_2/\gamma_2 < \sigma_3,$

then the energy intensity effect in Model 2 is higher than 0. Under the influence of capital input, the increase in energy efficiency will reduce the economic income effect and also the energy intensity effect. The reduction in the economic income effect and also the energy intensity effect is the reason for the weaker energy rebound effect in Model 2.

(3) Reduce the capital intensity effect will bring down the energy intensity effect, but whether the energy-capital substitutional effect will reduce remains uncertain. If $(1-\sigma_1)/\gamma_2 > \sigma_3$, the value of the energy-capital substitutional effect is positive, then capital input will not help to reduce the energy intensity; if $(1-\sigma_1)/\gamma_2 = \sigma_3$, the energy-capital substitutional effect is 0, then capital input will give no impact to energy intensity; if $(1-\sigma_1)/\gamma_2 < \sigma_3$, the value of the energy-capital substitutional effect is negative, then capital input will help to reduce the energy intensity.

From (13), we can get:

$$\frac{\partial \eta_h}{\partial \sigma_1} = \frac{1}{\sigma_3} > 0, \qquad \frac{\partial \eta_h}{\partial \sigma_3} = -\frac{\sigma_1}{\sigma_3^2} < 0, \qquad \frac{\partial \eta_h}{\partial \gamma_1} = -1. \tag{15}$$

Obviously, increasing the elasticity $\sigma_1$ between the economic income and energy consumption amount will lead to the increase in the energy rebound effect; increasing the elasticity $\sigma_3$ between economic income and labor will reduce the energy rebound effect; and increasing the elasticity $\gamma_1$ between energy consumption amount and energy efficiency will reduce the energy rebound effect.

According to the calculations from different models, we sum up the energy rebound effects as follows:

**Table 1.** Energy rebound effect based on different calculation models

| Energy efficiency | | | Economic income effect | Energy intensity effect | Energy saving |
|---|---|---|---|---|---|
| Exogenous | Short term | Saunders and Wei | $\sigma_1/(1-\sigma_2)$ | - | $\sigma_1/(1-\sigma_2)$ |
| | Long term | Wei | $\sigma_1/\sigma_3$ | - | $\sigma_1/\sigma_3$ |
| | Long term | Model 1 | $\sigma_1/\sigma_3$ | - | $\sigma_1/\sigma_3$ |
| Endogenous | Long term | Model 2 | $\sigma_1/\sigma_3-\gamma_1\sigma_2/\gamma_2\sigma_3$ | $\gamma_1\sigma_2/\gamma_2\sigma_3-\gamma_1$ | $\sigma_1/\sigma_3-\gamma_1$ |

## 3. Empirical Analysis

From equations (1) and (11), we can get the following estimator of the production function:

$$\ln Y = C_1 + C_2 t + C_3 \ln E + C_4 \ln K + C_5 \ln L + \varepsilon. \quad (16)$$

In this equation, $C_2$ represents technology innovation which cannot be expressed by energy efficiency.

Combining (1) and (10), we can get:

$$\sigma_1 - \frac{\sigma_1}{\gamma_1} = C_3, \quad \sigma_2 - \sigma_1 + \frac{\sigma_1}{\gamma_1} = C_4, \quad \sigma_3 = C_5, \quad \sigma_1 + \sigma_2 + \sigma_3 = 1. \quad (17)$$

Data sources and their definitions:

Energy consumption amount: Data from China Energy Statistical Yearbook; Unit: 10,000 tons equivalent coal;

Labor force: Labor force refers to all the practitioners society-wide. The data is from China Yearbook; Unit: 10,000 people;

Stock of capital: Stock of capital is represented by the amount of material capital. Its unit is 100,000,000 Yuan. Statistics between 1985-2004 is from Jun et al. [8]; statistics between 2004-2005 is from the database of the Research Center of Socialist Market Economy of Fudan University. This data was upgraded by Zhang Jun; the figure of 2006-2007 is based on calculation with the extrapolation method;

Economic output: The economic output refers to GNP (it is in line with stock of capital). Data from China Statistical Yearbook, Unit 100,000,000.

The regression function of equation (17) is:

$$LOGY=1.92699667843+0.0498223604435*T+0.146469695719*LOGE$$

$$(0.1167) \quad (0.0014) \quad (0.0009)$$

$$+ 0.323485018868*LOGK + 0.201675182083*LOGL$$

$$(0.0116) \quad (0.0517)$$

DW = 1.886126, $F$ = 21594.33, A.$R^2$=0.999745, AIC = –5.628402, Sqr = 0.003134.

From (16) and (17), we can get:

$$\sigma_1 = 0.3283, \quad \sigma_2 = 0.4700, \quad \sigma_3 = 0.2017, \quad \gamma_1 = 0.1465.$$

Table 2 lists the short-term energy savings from different models of calculation. From this table, we can find:

(1) Under the exogenous model, the short-term energy saving in our country is 0.4888, based on Saunders [1] and Wei's [7] calculation. However, this result is far different from Wang Qunwei's estimation of energy rebound, which is 60%, but it is still within the range of energy rebound, i.e., 30%-80%, as proposed by Zhou and Lin [5]. The disparity lies in the following 2 aspects: On one hand, based on energy efficiency increase, Saunders [1] and Wei [7] worked out the short-term energy saving, whereas Wang and Zhou [6] worked out the scale of energy rebound based on technological innovation. If Wang also worked out short-term energy saving, then the increase of energy efficiency is just one part of technological innovation. Thus, it is normal that Saunders [1] and Wei's [7] result is lower than that of Wang's; on the other hand, if Wang worked on the mid term or long term energy saving, then during the mid term or long term period, the energy saving thus calculated may be higher than short term energy saving due to the influence of capital.

(2) Under the exogenous model, the energy saving worked out under Model 1 is 1.6277, which is consistent with Wei's calculation of long term

energy saving. At present, the economic growth in our country relies heavily on energy consumption. The elasticity of energy is 0.3283, and the elasticity of labor force is 0.2017. The replacement elasticity between energy and labor force is over 1, which means it is easier to replace labor force with energy. The increase of energy efficiency does not affect the energy intensity per labor, but it improves the economic income per labor, which leads to the increase of the elasticity between energy consumption per labor and energy efficiency.

(3) Under the endogenous model, it is calculated that the energy efficiency is 0.2535, the economic income effect is 1.2277, and energy saving is 1.4812. Compared to Model 1, the impact of capital input leads to weaker economic income effect but stronger energy intensity effect. Meanwhile, the reduction in the economic income effect is greater than the increase of the energy intensity effect. This is the main reason why energy saving from Model 2 is lower than that from Model 1. Under the model where energy efficiency is an exogenous variable, if the impact to energy intensity effect by the increased energy efficiency is not considered, then the long term energy rebound amount may be overestimated in this model; if the impact of capital and labor force input is not taken into account, then the long term energy rebound amount may be underestimated. Model 2 assumes the energy efficiency is an endogenous variable and takes into account the impact of capital input. Relatively speaking, the calculation of long term energy saving from Model 2 may be more practical as it lies between Wei's [7].

(4) Whichever mode it is, its result shows the increased energy efficiency will lead to the reversed effect. Under the impact of capital input, the higher energy efficiency, the higher energy intensity will be. This is closed related to our nation's heavy dependence on capital input at present $(\sigma_2/\gamma_2 > \sigma_3)$. Reducing the capital elasticity or increasing the elasticity of the labor force will help to reduce the energy intensity effect. Reducing the capital intensity effect and energy-capital substitutional effect will bring down the energy intensity effect.

**Table 2.** Energy savings based on different models

| Energy efficiency | | | Economic income effect | Energy intensity effect | Energy saving |
|---|---|---|---|---|---|
| Exogenous | Short term | Saunders and Wei | 0.4888 | - | 0.4888 |
| | Long term | Wei | 1.6277 | - | 1.6277 |
| | Long term | Model 1 | 1.6277 | - | 1.6277 |
| Endogenous | Long term | Model 2 | 1.2277 | 0.2535 | 1.4812 |

## 4. Conclusion

Based on the above analyses, we can draw the following conclusions:

(1) Assume energy efficiency is an endogenous variable, the calculation model of long term energy rebound effect divides energy saving into economic income effect and energy intensity effect which is in turn divided into energy-capital substitutional effect and capital intensity effect. It points out that energy efficiency brings about energy rebound effect. This is the distinctive feature of this model and empirical analyses show this model is closer to the fact.

(2) The reverse effect of energy efficiency has long been in existence in China. Under the influence of capital input, the improvement in energy efficiency did not reduce energy intensity effect, but rather increased it. This was mainly because the economic growth in China largely relies on capital and energy.

(3) Reducing the capital intensity effect and energy-capital substitutional effect will help to bring down the energy intensity effect.

(4) Reducing the dependence on energy and capital input will help to reduce the energy rebound effect.

(5) Increasing the elasticity between the economic income and the labor force, and also the elasticity between the energy consumption amount and energy efficiency will help to reduce the energy rebound effect.

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