Renewable and Sustainable Energy Reviews 74 (2017) 258–264

Contents lists available at ScienceDirect

Renewable and Sustainable Energy Reviews

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

The relationships among energy consumption, economic output and energy intensity of countries at different stage of development

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ARTICLE INFO

Keywords:
Energy consumption
Economic output
Energy intensity
Growth rate
3 GR model

ABSTRACT

Based on 3GR model, the relationships between energy consumption, economic effect and technical effect of countries at different stage of development (developed, developing and the least developed countries) was figured out. Comparing the equivalent value of *GREC*, *GREO* and *GREI* during the period from 1996 to 2013, the diverse development laws in different kinds of countries was found. The following conclusions were obtained: (1) based on 3GR model, there is a liner relationship between *GREC* and *GREO* or *GREI* and an inverse relationship between *GREI* and *GREO* when the equivalent value of $(1+GREO_i)$ or $(1+GREI_i)$ or $(1+GREC_i)$ is a constant. (2) The equivalent value of *GREO* are in the following orders, developed countries < developing countries < the least developed countries, while that of *GREI* have the opposite orders. The orders of the equivalent value of *GREC* are developed countries, the least developed countries and developing countries from small to large. The least developed countries own the largest potential to realize further development whether in economic expansion, technical innovation or in optimize industrial structure while these potential in developed countries are the smallest and in developing countries are at the middle level; the development in developing countries shows the most growth going forward. (3) The change in energy consumption is codetermined by *EO* effect, *EI* effect and their interactive effect. *EO* effect shows the leading position among the three effects, especially in developing countries and the least developed countries. In developed countries, *EC* change, *EO* effect and *EI* effect are both change in a tight range. While in developing countries and the least developed countries, these ranges are rather large.

1. Introduction

In recent decades, energy consumption in the world increased rapidly since energy is essential for economic growth [1]. At the same time, excessive fossil energy consumption is causing a serious of environmental problems [2]. E.g. the global acid rain problem, the Antarctic ozone hole problem and global warming. How to reduce the energy consumption is a hot issue. In order to cut down total energy consumption, reducing energy intensity has been thought as the most cost-effective ways [3]. Energy intensity, which is usually quantified by energy-to-gross domestic product ratio [4–6], is affected by two main factors, technical innovation and industrial structure [4,7]. Most of enterprises innovate technology to respond the challenges of pressure on energy supply. Meanwhile, government has been committed to optimizing industrial structure by restricting the development of energy-intensive enterprises [8]. Thus, there are some complex relations among energy consumption, economic growth, and energy intensity.

The volume of published literature on these relations has been increasing in recent years. These studies analyzed their relations and were usually base on a single area, such as a country, a state or a city [8–11]. From the perspective of their growth rate, this paper analyzes relations of their growth rates in several countries. In detail, the growth rate of energy consumption, economic output and energy intensity are abbreviated as *GREC*, *GREO* and *GREI*, respectively.

For countries at different development stage, their values of *GREC*, *GREO* and *GREI* vary. The least developed countries are at a low level whether in economic expansion, technical innovation or in optimize

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http://dx.doi.org/10.1016/j.rser.2017.02.055
Received 23 July 2016; Received in revised form 10 December 2016; Accepted 12 February 2017
1364-0321/

industrial structure [12]. In developed countries, the core of the world economy [13], their economy is highly developed and technology is advanced [14]. Their developments are entering a bottleneck period because further developments are constrained by natural resources and environmental issues [2]. The development degree of developing countries is between developed countries and the least developed countries.

There are two aspects of the objective in this investigation. Firstly, 3GR model states the relationship among *GREC*, *GREO*, and *GREI*, in theory [15]. It is meaningful to discuss its practicability. Secondly, based on 3GR model, it is valuable to analyze the regularity of *GREC*, *GREO*, and *GREI* of different types of countries. The results could help us to find out the different influence of economic output and energy intensity on energy consumption.

The framework structure was built as follows. Section 2 introduced the method of 3GR model, including the data source, the selected countries and the indicators. Section 3 plotted the isograms of growth rate and the cumulative growth rate, and then compared the growth rate of economic output, energy intensity and energy consumption in different countries. Section 4 discussed the reasons that caused these differences. Section 5 drew conclusions.

2. Methods and data

2.1. 3GR model

Many literatures use Cobb-Douglas production function to analyze the relationship between energy consumption and economic growth [14,16–18]. Cobb-Douglas production function showed the level of production is explained by capital, labor and other determinants of economic growth [19]. While many causality tests demonstrate that, the causality between economic growth and energy consumption is bidirectional [11,20,21]. To clarify this relationship, we used 3GR model, which explains the trilateral relations among energy consumption, energy intensity and economic output and their pairwise correlations from the perspective of growth rate.

The fundamental formula of 3GR model is deduced from the quantification of energy intensity (energy-to-gross domestic product ratio), shown as Eq. (1) [15].

$$(GREC_i + 1) = (GREO_i + 1)(GREI_i + 1). \tag{1}$$

Where, $GREC_i$, $GREO_i$ and $GREI_i$ is the growth rate of energy consumption, economic output and energy intensity in i^{th} year, respectively; they are non-dimensional.

Growth rate of economic output, energy consumption, energy intensity are calculated by Eq. (2) [15],

$$GR_i = (x_i - x_{i-1})/x_{i-1}. \tag{2}$$

Where, x_i is the value of economic output or energy consumption or energy intensity in the i^{th} year. GR_i is the growth rate of corresponding value, such as *GREI*, *GREO*, and *GREC*.

The equivalent value of *GREI*, *GREO*, and *GREC* in research period is defined as Eq. (3) [15],

$$EV_{GR} = \sqrt[n-1]{\prod_1^n (GR_j + 1)} - 1. \tag{3}$$

Where, EV_{GR} is the equivalent value of *GREC*, *GREO* and *GREI*; they are non-dimensional. The sub-index 1 refers to the first year (1996) in the research period. n is the research period, it equal to eighteen years.

Based on the Eq. (1) and some hypothesizes, Eq. (4), Eq. (5), and Eq. (6) could be obtained. According to Eq. (3), the equivalent value of *GREO* in the research period can be calculated. And it is reasonable to assume that (1+$GREO_i$) in Eq. (1) equals to the equivalent value of *GREO* plus one. Thus, there is a linear relationship between *GREC* and *GREI*, and the slope of line is determined by *GREO*, shown as Eq. (4) [15],

$$GREC_i = k_1 GREI_i + (k_1 - 1) \tag{4}$$

Similarly, the equivalent value of *GREI* and *GREC* in the research period could be calculated, Eq. (5) and Eq. (6) could be obtained [15],

$$GREC_i = k_2 GREO_i + (k_2 - 1). \tag{5}$$

$$GREO_i = k_3/(GREI_i + 1) - 1. \tag{6}$$

Based on the Eq. (3), there is a multiple multiplication relationship as Eq. (7) shown [15],

$$\prod_1^i (GREC_j + 1) = \prod_1^i (GREO_j + 1) \times \prod_1^i (GREI_j + 1). \tag{7}$$

Where, k_1, k_2 and k_3 are some constants, which equal to the equivalent value of *GREO*, *GREI*, and *GREC* plus one, respectively. Symbol '∏' means multiplying one by one. In order to analysis the effects of each factor on energy consumption, the equivalent value of energy consumption is defined as Eq. (8),

$$EV_{EC} = \frac{(EC_1 - EC_0) + \frac{(EC_2 - EC_0)}{2} + \cdots + \frac{(EC_i - EC_0)}{i} + \cdots + \frac{(EC_n - EC_0)}{n}}{n} \tag{8}$$

Where, EV_{EC} represents the equivalent value of annual energy consumption; EC_i is annual energy consumption in i^{th} year. Their unit is tons of *SCE*.

Both economic output and energy intensity play important roles on energy consumption. In order to reflect the their influence on energy consumption, Eq. (9) and Eq. (10) are introduced,

$$EV_{EC-EO} = \frac{(EO_1 - EO_0) \times EI_0 + \frac{(EO_2 - EO_0) \times \frac{EI_0 + EI_1}{2}}{2} + \cdots + \frac{(EO_i - EO_0) \times \frac{EI_0 + EI_1 + \cdots + EI_{i-1}}{i}}{i} + \cdots + \frac{(EO_n - EO_0) \times \frac{EI_0 + EI_1 + \cdots + EI_{n-1}}{n}}{n}}{n} \tag{9}$$

$$EV_{EC-EI} = \frac{(EI_1 - EI_0) \times EO_0 + \frac{(EI_2 - EI_0) \times \frac{EO_0 + EO_1}{2}}{2} + \cdots + \frac{(EI_i - EI_0) \times \frac{EO_0 + EO_1 + \cdots + EO_{i-1}}{i}}{i} + \cdots + \frac{(EI_n - EI_0) \times \frac{EO_0 + EO_1 + \cdots + EO_{n-1}}{n}}{n}}{n} \tag{10}$$

Where, $EV_{EC\text{-}EO}$ and $EV_{EC\text{-}EI}$ is the equivalent value of energy consumption caused by *EO* effect and *EI* effect (abbreviated terms in section3.4.1), respectively. Their unit is tons of *SCE*. EO_i is annual economic output in the i_{th} year. Its unit is $. EI_i is annual energy intensity in the i_{th} year. Its unit is tons of SCE per $.

Besides, the interactive relationship between *EO* effect and *EI* effect would also influenced total energy consumption. This interactive influence on energy consumption is an unknown function, thus, an identity is derived as Eq. (11) shows.

$$EV_{EC} = EV_{EC-EO} + EV_{EC-EI} + f(EV_{EC-EO}, EV_{EC-EI}) \tag{11}$$

Where, $f(EV_{EC\text{-}EO}, EV_{EC\text{-}EI})$is the unknown function which represents the interactive influence on energy consumption. $EV_{EC\text{-}EO}$, $EV_{EV\text{-}EI}$, and $f(EV_{EC\text{-}EO}, EV_{EC\text{-}EI})$ would be positive or negative, EV_{EC} is the product of their effect canceled each other. In order to directly compare *EO* effect and *EI* effect on energy consumption, their absolute share in energy consumption is calculated by Eq. (12), Eq. (13) and Eq. (14),

$$P(EV_{EC-EO}) = \frac{|EV_{EC-EO}|}{|EV_{EC-EO}| + |EV_{EC-EI}| + |f(EV_{EC-EO}, EV_{EC-EI})|} \times 100\% \tag{12}$$

$$P(EV_{EC-EI}) = \frac{|EV_{EC-EI}|}{|EV_{EC-EO}| + |EV_{EC-EI}| + |f(EV_{EC-EO}, EV_{EC-EI})|} \times 100\% \tag{13}$$