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A novel evolution tree for analyzing the global energy consumption structure

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ABSTRACT

Systematically organizing and analyzing the energy consumption structure of the world can reveal the organic connections between countries. Furthermore, such tasks can provide a global reference system for each country, enabling each one to adjust and optimize its energy consumption structure. Most previous studies of the global energy consumption structure overlooked the associations between countries and the evolutionary trends associated with the energy consumption structures of countries. This paper analyzes the evolution of the global energy consumption structure using an evolution tree model. The visual structure of this model provides a novel perspective for understanding and analyzing the underlying trends. First, 144 countries and regions are categorized into four different types using the k-means clustering algorithm. Countries and regions that belong to the same type generally follow similar evolutionary paths. Moreover, type IV countries, which are mainly developed countries, have the most diverse energy consumption structures. By contrast, the energy consumption structures of other types of countries and regions can be improved. Countries can be located in the global energy consumption structure of the evolution tree, and these locations can provide a basis for improving the energy consumption structure of a country based on similar countries that are more diverse.

1. Introduction

The energy consumption structure refers to the percentage of each type of energy consumed (such as coal, petroleum, natural gas, nuclear power, and other renewable energy) relative to the total energy consumption [1]. The energy consumption structure is one of the most important indicators used to measure the development level of a country or region [2]. Energy consumption structures vary based on the energy conditions in each country. For instance, because of the abundant oil and gas resources in the Middle East, the energy consumption structures of Middle Eastern countries mainly consist of petroleum and natural gas. In the Asia-Pacific region, countries such as China and India have abundant coal resources; thus, coal accounts for large proportions of their energy consumption structures. Furthermore, in post-industrial societies, some developed countries are moving toward low-power, high-yield industrial structures, and their energy-related technologies are becoming more advanced. Therefore, they are diversifying their energy consumption structures [3]. However, fossil fuels are a type of non-renewable energy that causes serious damage to the environment [4,5]. Therefore, a lot of countries have tried to adjust their energy consumption structures and introduce more renewable energy [6,7]. For example, the Chinese government has announced plans to develop a low-carbon economy and has set a target to increase its share of non-fossil energy to 15% of total energy consumption by 2020 [8]. In addition, hybrid renewable energy systems (HRES) that typically consist of two or more renewable energy sources (e.g., solar, wind, rain, tidal, wave, and geothermal heat energy sources) are becoming popular in several countries due to advances in renewable energy technologies [9,10]. Furthermore, microgrids composed of large numbers of on-site distributed energy resources are also expected to increase the use of renewable energy sources and to thus reduce CO_2 emissions [11,12]. Evolutional analyses of the energy consumption structures of most countries can not only help in determining the adjustment of the energy consumption structure in a particular country but also provide a framework within which countries can learn from other countries with similar backgrounds but superior energy

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consumption structures.

Few studies have focused on energy consumption structures at the international level. Wang et al. [13] used a center of gravity theory to study the spatial distributions and centers of gravity of the global energy supply and energy consumption to determine how they have changed over time. They found that the center of gravity for oil consumption has shifted toward the southeast, while natural gas consumption has shifted toward the east. Lawrence et al. [14] studied the global probability distribution of energy consumption per capita around the world. They found that the Gini coefficient, G, decreased from 0.66 in 1980 to 0.55 in 2010, indicating a decrease in inequality. The global probability distribution of energy consumption per capita in 2010 was close to an exponential distribution, with $G = 0.5$, which indicates that the top 1/3 of the world population consumes 2/3 of the produced energy. Chen and Chen [15] analyzed the global energy issue using a systematic input-output simulation and found that the United States is the world's largest embodied energy importer and embodied energy surplus receiver. By contrast, China is the largest exporter and deficit receiver. Fujimori S et al. [16] performed global energy model hindcasting using one of the integrated assessment models. They found that the global aggregated primary energy exhibits high reproducibility and that high-income countries tend to exhibit higher reproducibility compared to low income countries. Based on entropy information, Zhang et al. [17] evaluated the evolution of China's energy consumption structure and noted the slow improvement in Chinese energy consumption. However, the links between energy consumption in different countries have been overlooked in previous analyses, and the evolution of the global energy consumption structure requires further exploration.

The evolution tree method was first used to analyze the evolutional pathways of growing cities and forecast urban development and spatial expansion [18]. Liao et al. (2013) used the evolution tree approach to estimate the prevalence of disability caused by unintentional injury among people from 15 to 60 years old in different cities in the People's Republic of China [19]. Zhang and Zhang [20] used the evolution tree method to analyze the evolution of sustainable development in the Yangtze River Delta region, China. The present study provides an application and extension of the evolution tree approach to analyze the global energy consumption structure.

In this paper, we focus on the issues noted above, specifically the links between the energy consumption structures of different countries and the underlying evolutionary trends. The study applies the evolution tree model to 144 countries and regions using data from 2000 to 2010. The practical advantages and engineering value of the proposed method are as follows: (1) The evolution tree of the global energy consumption structure provides a global reference system for each country with which each one can adjust and optimize its energy consumption structure. (2) The evolution tree model can reveal the connections between countries. (3) The engineering value of the proposed model is that it provides countries with a visual tool for understanding and analyzing the underlying evolution trends of the energy consumption structures in different countries.

The contributions of this paper are threefold. First, to our knowledge, this is the first paper to analyze the evolution of the global energy consumption structure. A total of 144 countries and regions are studied to explore the evolution of the overall energy consumption structures. Second, this paper applies the evolution tree model to the energy domain for the first time. Third, the evolution tree model provides a novel perspective for observing, exploring and analyzing the evolution of the energy consumption structure.

The remainder of this article is organized as follows. In Section 2, we describe the data set and explain why we use these data. In Section 3, we provide a detailed description of the evolution tree model of the energy consumption structures of 144 countries and regions. Then, we build a Markov chain based on the evolution tree. Section 4 analyzes the evolution of the energy consumption structure based on the evolution tree and the Markov chain. In Section 5, we interpret the evolution results obtained in the preceding section and provide suggestions regarding how to use our model to adjust the energy consumption structures in various countries. Finally, the main conclusions of the paper are summarized.

2. Materials

In this study, we use the gross domestic product (GDP) per capita (constant 2005 value in USD) and economic structure data from 144 countries and regions as clustering factors. Data from 2000 to 2010 were obtained from the Jobs Database of the World Bank [21–23]. In addition, energy consumption data, including petroleum, coal, natural gas, nuclear, hydroelectric and other renewable energy (million tons of oil equivalent) data, from 2000 to 2010 were collected from the United States Energy Information Administration (EIA) [24,25].

2.1. GDP per capita

Fig. 1 shows the GDP per capita of 144 countries and regions. Some countries are blank due to the lack of data. The illustration indicates that most countries in Europe and North America have very high GDP per capita values, while countries in South America and Australia exhibit moderate values. Additionally, countries in Asia and Africa have low GDP per capita values.

Numerous studies have noted that there is a strong relationship between the energy consumption structure and GDP [26–29]. In the process of economic development, the GDP growth rate of a country generally exhibits the same trend as its energy consumption growth rate [30].

2.2. Economic structure

Fig. 2 shows that countries in Europe, North America, South America and Australia have very similar economic structures. In those countries, the value added by tertiary industry accounts for the largest proportion of the GDP, followed by the value added by secondary industry and that added by primary industry. Some countries in southern Africa also exhibit these characteristics. In Asia, most countries have similar value-added contributions from secondary and tertiary industries, and the value added by primary industry constitutes a relatively high proportion of the total GDP. However, in central Africa, West Asia and Southeast Asia, the value added by secondary industry constitutes a very high proportion of the total GDP. In North Africa and West Africa, the economic structures of some countries mainly rely on primary industry.

The value added by secondary industry has the largest influence on the energy consumption structure [31,32]. Tertiary industry has a lower energy intensity than secondary industry [33]. Because secondary industry accounts for 30–70% of the total global energy consumption, it consumes more fossil fuels than tertiary industry [34,35]. Thus, the economic structure has a significant relationship with the energy consumption structure.

2.3. Energy consumption structure

Fig. 5 shows the energy consumption structures of 144 countries and regions in 2000 and 2010. In most countries, oil accounted for