Energy 147 (2018) 1177–1187

Contents lists available at ScienceDirect

Energy

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

A novel evolution tree for analyzing the global energy consumption structure

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ARTICLE INFO

Article history:
Available online 4 February 2018

Keywords:
Energy consumption structure
Evolution tree
Cluster analysis
Markov chain

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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https://doi.org/10.1016/j.energy.2018.01.093
0360-5442/

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

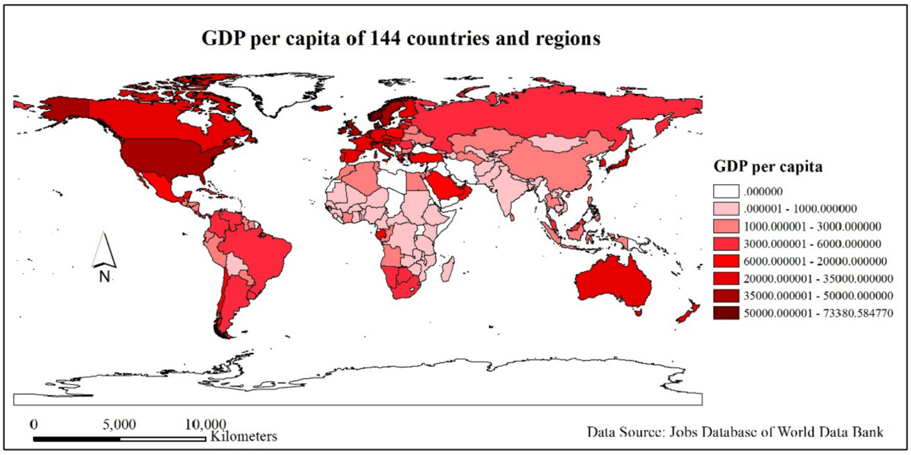


Fig. 1. GDP per capita of 144 countries and regions.

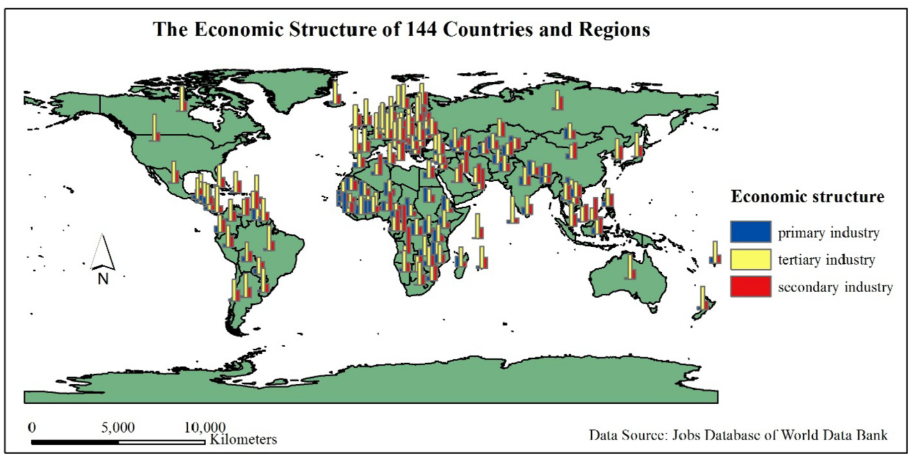


Fig. 2. Economic structures of 144 countries and regions.

the largest proportion of the energy consumption structure, followed by natural gas. However, it is difficult to accurately interpret the energy consumption structure in each country and determine the difference between energy consumption in 2000 and that in 2010. Therefore, we built an evolution tree of the energy consumption structures of 144 countries and regions. This tree can be used to identify the underlying evolutional trends.

3. Methodology

The evolution tree model was first introduced by Wang and used to explore the evolutional pathways of growing cities [18]. In this paper, we establish a geographic evolution tree model to study the evolution of the energy consumption structures of 144 countries and regions in 2000 and 2010. First, we cluster the 144 countries and regions into four types using a clustering method (Section 3.1). Next, we create a method for expressing the energy consumption structure based on main energy types and subordinate energy types (Section 3.2). Then, we describe the process of building and coding the evolution tree (Section 3.3). Finally, we establish a Markov chain based on the evolution tree (Section 3.4). Fig. 3 shows the flow diagram of the proposed method.

3.1. Clustering of countries

The k-means clustering method is applied to cluster the 144 countries and regions into four country types [36]. The GDP per capita data and economic structure data are used as the clustering factors. Before clustering, we normalize the GDP per capita in the interval of [0, 1] using the min-max normalization method. This process makes the clustering result more accurate and reliable. k-means clustering identifies k clusters, which is the only parameter in the evolution tree model. The number of clusters most appropriate for a data set—four in this case—is determined using the gap statistic method [37].

Observations of the 144 countries and regions are denoted as $(x_1, x_2, \cdots, x_{144})$, where each observation is a 4-dimensional vector. k-means clustering aims to partition the 144 observations into $k(\leq 144)$ sets $S = \{S_1, S_2, \cdots, S_k\}$ to minimize the within-cluster sum of squares (WCSS). Formally, the objective is to find:

$$\underset{S}{\operatorname{argmin}} \sum_{i=1}^{k} \sum_{x \in S_i} x - m_i = \underset{S}{\operatorname{argmin}} \sum_{i=1}^{k} |S_i| Var\, S_i \tag{1}$$

where m_i is the mean of points in S_i.

Given an initial set of k means $(m_1, m_2, \cdots, m_k)$, the algorithm proceeds by alternating between two steps:

(1) Assignment step: Assign each observation to the cluster whose mean yields the lowest WCSS.

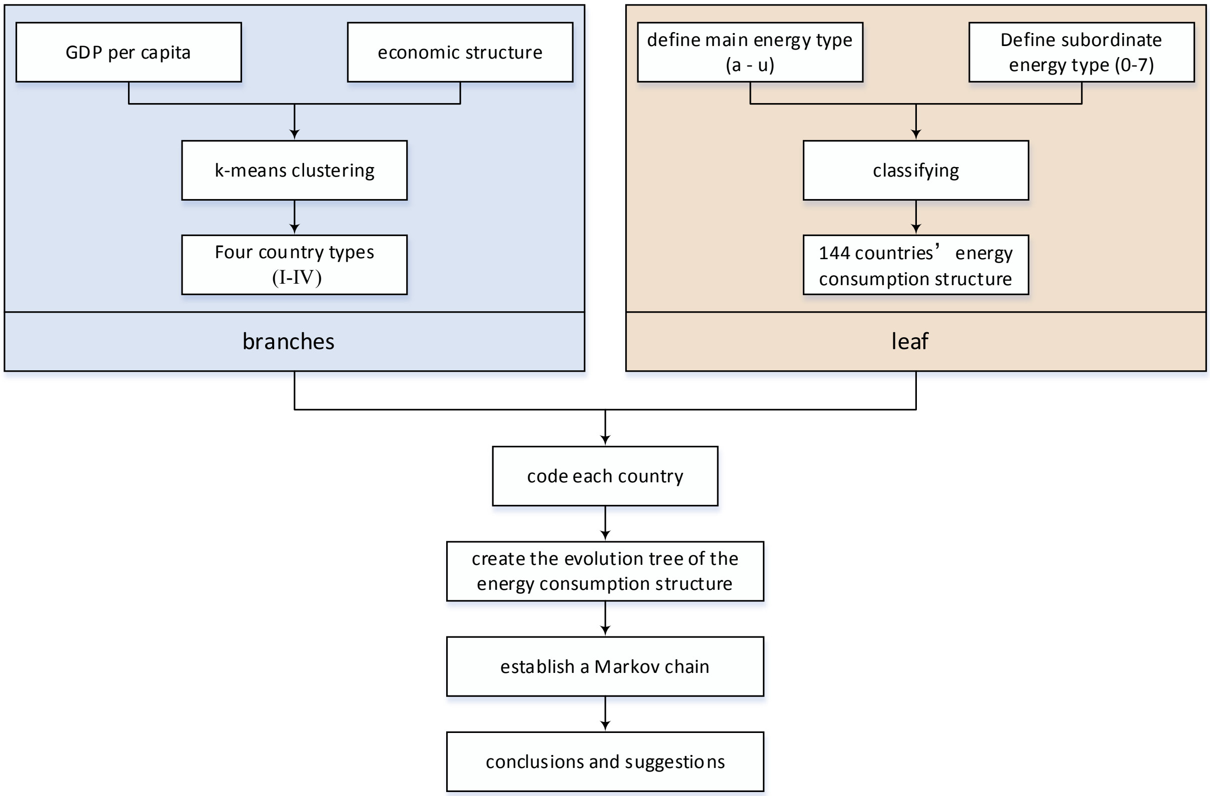


Fig. 3. Flow diagram of the proposed method.

$$S_i^{(t)} = \left\{ x_p : x_p - m_i^{(t)2} \le x_p - m_j^{(t)2} \; \forall j, 1 \le j \le k \right\} \tag{2}$$

where each x_p is assigned to exactly one $S^{(t)}$.

(2) Update step: Calculate the new means that will serve as the centroids of the observations in the new clusters.

$$m_i^{(t+1)} = \frac{1}{\left|S_i^{(t)}\right|} \sum_{x_j \in S_i^{(t)}} x_j \tag{3}$$

The algorithm converges when the assignments no longer change.

Table 1 presents the four country types identified via this process. The arithmetic mean and standard deviation are calculated for each clustering variable. We label the four country types as I-IV. Fig. 4 shows the spatial distribution of the four country types. The four country types can be summarized as follows.

Type I: In this country type, the proportions of the values added by primary industry and tertiary industry are high, and the proportion added by secondary industry is relatively low. Additionally, the GDP per capita is low. These countries can be characterized as having low levels of industrialization and poor economies. They are mainly distributed in western, southern and central Asia (e.g., India and Pakistan) and eastern, western and central Africa (e.g., Central African Republic and Ethiopia).

Type II: In this country type, the proportions of the values added by secondary industry and tertiary industry are high, and the proportion added by primary industry is relatively low. Additionally, the GDP per capita is low. These countries can be characterized as having relatively developed industries but poor economies. They are mainly distributed in eastern and Southeast Asia (e.g., China and Thailand), northern and central Africa, and Latin America.

Type III: In this country type, the proportion of the value added by tertiary industry is very high, followed by the value added by secondary industry. The value added by primary industry is low, as is the GDP per capita. These countries are mainly distributed in Latin America and southern Africa. The Russian Federation belongs to this country type.

Type IV: In this country type, the proportion of the value added by tertiary industry is extremely high, followed by the value added by secondary industry. The proportion of the value added by primary industry is small. However, the GDP per capita in these countries is extremely high. Most of these countries are developed countries that have entered the post-industrial stage. The majority of these countries are distributed in Europe and North America, and Australia is included in this group.

3.2. Main and subordinate energy types

In this paper, we define the main and subordinate energy types to more effectively represent the energy consumption structure. The main energy consumption types are defined as energy types that account for more than 60% of the total energy consumption. Two situations exist: in one, the proportion of a single energy source is higher than 60%; in the other, a combination of several energy sources that have similar proportions accounts for more than 60% of the total energy consumption. We choose 60% as a threshold because of the following: (1) If an energy source's proportion is higher than 60%, then the proportions of all other energy sources are less than 40%. In this case, there is no doubt that the energy source whose proportion is higher than 60% can be considered as the main energy type of a country. In more than half of the countries and regions (79 out of 144), the proportion of a

Table 1
Means and standard deviations of four types of countries (SD for standard deviation).

Country type	Number of countries	Statistic	Clustering factors			
			Primary industry	Secondary industry	Tertiary industry	GDP per capita
Type I	34	Mean	0.30	0.21	0.49	0.01
		SD	0.10	0.06	0.07	0.01
Type II	35	Mean	0.10	0.48	0.42	0.07
		SD	0.07	0.11	0.08	0.09
Type III	49	Mean	0.07	0.28	0.66	0.08
		SD	0.04	0.06	0.07	0.06
Type IV	26	Mean	0.02	0.23	0.75	0.50
		SD	0.02	0.07	0.08	0.16

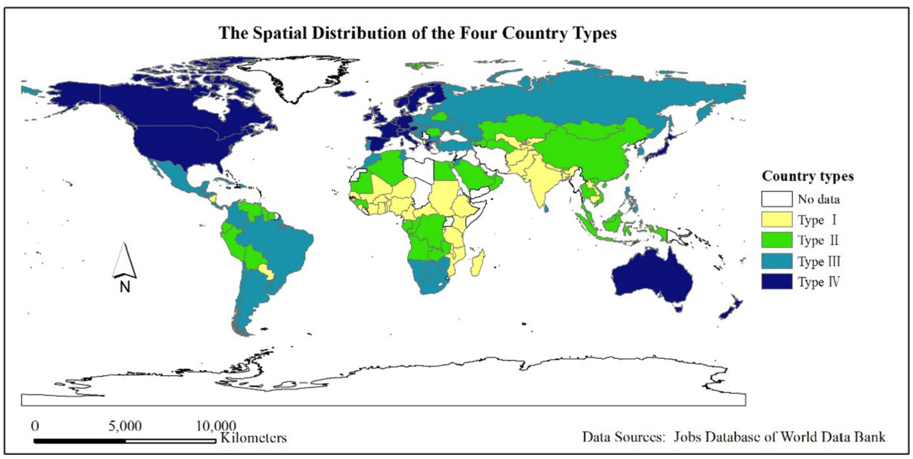


Fig. 4. Spatial distribution of the four country types.

single energy source is higher than 60%. (2) It is inappropriate to choose 50% or 70% as the threshold. In the case of 50%, there may be another energy source whose proportion is less than but close to 50%. In that case, it is not suitable to choose the higher one as the main energy type. However, in the case of 70%, there may be an energy source whose proportion is less than 70% but more than 60%. In this case, we would have to find another energy source so that the sum of the proportions of the two energy sources is in excess of 70%, which is clearly ridiculous. Therefore, 60% can be viewed as a more practical threshold.

To include the remaining energy sources, subordinate energy types are defined as all other types of energy consumption in a country. However, energy sources whose proportions are less than 5% are ignored. The main energy types and subordinate energy types together account for more than 90% of the total energy consumption.

Based on these definitions, the main energy types of 144 countries and regions are classified into 21 categories. Categories are represented by a series of letters from 'a' to 'u' (see Table 2). The letters from 'a' to 'd' denote the four main energy types that have only one energy source. Therefore, the energy source denoted by each of these letters accounts for more than 60% of the total energy consumption of a country. The letters from 'e' to 'k' denote main energy types that have two energy sources. The letters from 'l' to 'q' denote main energy types that have three energy sources. The letters from 'r' to 't' denote main energy types that have four energy sources. The letter 'u' denotes a main energy type with five energy sources. A main energy type with more energy sources indicates that the energy consumption structure of a country is more balanced. The subordinate energy types are denoted by numbers from 0 to 7 (see Table 3). Therefore, the combination of a letter and several numbers in the evolution tree reflects the energy consumption structure of country and represents more than 90% of the total energy consumption of that country.

3.3. Coding of the evolution tree

In the evolution tree model of energy consumption, the energy consumption structures of countries are arranged in a treelike structure. The branches correspond to country types (Roman numerals in the coding system described above), and each leaf represents a country and its energy consumption structure classification code (see Fig. 5). Each country is assigned a letter-digit code based on its classification. The first three capital letters of this code denote the abbreviation of a country. The subsequent Roman numeral denotes the country type (I-IV, see Table 1). The subsequent pairwise combination of a letter and one or two digits represents the energy consumption structure in 2000 and 2010. A color change between the left semicircle and right semicircle reflects a change in the main energy type between 2000 and 2010. The arrangement of the countries along the branches is based on the GDP per capita; countries with higher GDP per capita values are located closer to the stem.

For example, the code "CHN II c3c3" denotes China, a type II country whose main energy type was coal and subordinate energy type was petroleum in 2000. The energy consumption structure of China did not considerably change between 2000 and 2010. The code "IDN II a12l7" denotes Indonesia, a type II country whose main energy type was petroleum and subordinate energy types were natural gas and coal in 2000. However, the main energy type of Indonesia shifted to natural gas, coal and petroleum in 2010, and its subordinate energy types changed to other energy sources. Such

Table 2
Main energy types.

Main energy types (accounting for more than 60% of the total energy consumption)	
a	petroleum
b	natural gas
c	coal
d	hydroelectric
e	petroleum, natural gas
f	petroleum, hydroelectric
g	petroleum, coal
h	petroleum, nuclear
i	natural gas, hydroelectric
j	natural gas, coal
k	coal, hydroelectric
l	natural gas, coal, petroleum
m	natural gas, petroleum, nuclear
n	natural gas, petroleum, hydroelectric
o	petroleum, nuclear, hydroelectric
p	coal, petroleum, hydroelectric
q	petroleum, hydroelectric, other renewable energy
r	natural gas, coal, petroleum, nuclear
s	natural gas, coal, petroleum, hydroelectric
t	natural gas, petroleum, nuclear, hydroelectric
u	natural gas, coal, petroleum, nuclear, hydroelectric

Table 3
Subordinate energy types.

Subordinate energy types	
0	None or can be ignored (<5%)
1	natural gas
2	coal
3	petroleum
4	nuclear
5	hydroelectric
6	other renewable energy
7	other (including several energy sources that sum to less than 15% of the total consumption)

changes in the main energy type are denoted by color changes in some circles. The change in Indonesia indicates that they began to rely less on oil and that the consumption of natural gas and coal increased, resulting in a more balanced energy consumption structure.

3.4. Markov chain

The essence of a Markov chain is the probability of transition from one state to another state. This concept was applied to our proposed method.

In this study, we established a Markov chain based on the evolution tree of the energy consumption structure. The Markov chain (see Fig. 7) uses the coordinate system defined by the evolution tree to illustrate the pathways and numbers of countries whose main energy types change along the tree's branches. Some countries move along a single branch to a more diversified main energy type, although most countries do not move. For example, in the third branch (type III), 18 countries with petroleum as the main energy type remained unchanged, eight countries moved along the branch to a more diversified main energy type and a few countries shifted from one branch (or country type) to another (represented by the dashed lines in Fig. 7) .

4. Results

The evolution tree and Markov chain can be used to determine the evolution of the global energy consumption structure.

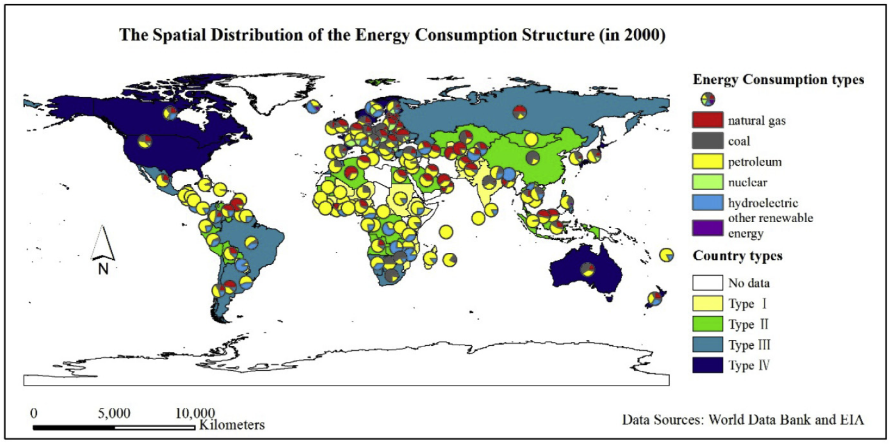
First, we analyze the global pattern of the energy consumption structure. Fig. 8 illustrates that petroleum (a) is the main energy type in most countries, including 42% of countries in 2000 and 37.5% in 2010. This characteristic is also obvious in type I countries and type III countries (see Figs. 6 and 7). Countries in which petroleum and natural gas (e) are the main energy types are the second most common in Fig. 7. These countries include Thailand, Denmark and the United Kingdom. Natural gas (b) is the third most common type of main energy. Countries in which natural gas is the main energy type include the United Arab Emirates, Belarus and Turkmenistan. Petroleum and hydroelectric (f) are the fourth most common main energy types. These main energy types are predominant in countries such as Brazil, Uruguay and Albania. Countries whose main energy types consist of several energy sources are in the minority. Eighty-two percent of the main energy types in these countries do not change between 2000 and 2010, as illustrated by the evolution tree, in which most circles are one color. Additionally, most arrows in the Markov chain point from a circle to itself rather than to another circle. Overall, 88.5% of countries whose main energy type is petroleum did not change between 2000 and 2010. This phenomenon is likely because these countries have abundant petroleum resources and petroleum infrastructures. Thus, the main energy types of these countries are unlikely to change within a decade. For example, Middle Eastern countries have abundant oil resources; therefore, their main energy type is petroleum. These countries, such as Saudi Arabia and Kuwait, did not change between 2000 and 2010. Similarly, China has abundant coal resources; thus, coal is the main energy type of China. Coal consumption barely changed, increasing from 68% of the total consumption in 2000 to 69% in 2010. However, of the countries in which the main energy type changed between 2000 and 2010, 70% shifted from a single main energy type to a more diversified main energy type. This trend is illustrated by the Markov chain (see Fig. 7), in which the arrows on the right sides of circles point from single main energy types to more diversified main energy types and arrows on the left sides of circles point in the opposite direction.

Second, the trends associated with each country type are discussed based on the evolution tree (see Fig. 6) and Markov chain (see Fig. 7).

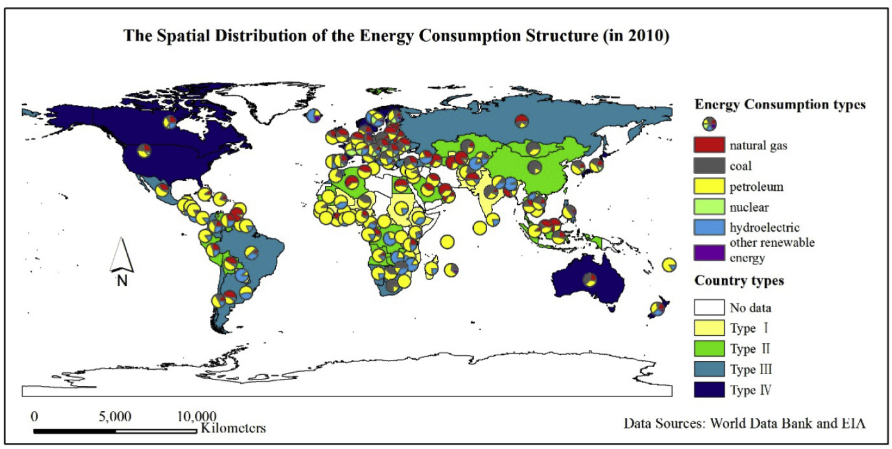
Regarding country type I, the main energy types are simple, and most countries heavily consume oil in their energy consumption structures. Five of the thirty-four type I countries changed their main energy types between 2000 and 2010. Two of these five improved their energy consumption structures by diversifying, while the others became less diverse. Moreover, the country types of five countries changed, with one shifting to country type III and the others shifting to country type II.

Regarding country type II, the most common main energy type is oil, followed by natural gas. The energy consumption structures of these countries are relatively simple, but the structures change frequently. Seven of the thirty-five type II countries changed their main energy types, and four diversified their energy consumption structures. For instance, Armenia greatly increased the proportions of clean energy, nuclear and hydroelectric and shifted away from an energy consumption pattern based on oil and natural gas. The main energy type in Mongolia was oil in 2000, but it shifted to coal in 2010, with oil becoming a subordinate energy type. This change is related to the amount of coal mining in the country. In addition, three countries shifted to country type III.

Petroleum is the most common main energy type in country type III. However, changes in the main energy type are more common. Ten countries changed their energy consumption structures. Eight became more diverse, and only two became less diverse. Notably, countries with diverse energy consumption



(a)



(b)

Fig. 5. Spatial distribution of the energy consumption structure in (a) 2000 and (b) 2010.

structures remained diverse. For instance, Slovenia maintained a diverse energy consumption structure consisting of natural gas, coal, petroleum, nuclear and hydroelectric between 2000 and 2010.

Regarding country type IV, countries whose main energy type is petroleum are no longer in the majority. Most countries in this type have diverse energy consumption structures, and few of them change. Therefore, they maintain their diverse energy consumption structures very well. For example, Switzerland has an energy consumption structure based on petroleum, nuclear and hydroelectric. The energy consumption structure of Japan is based on gas, coal, petroleum and nuclear. Additionally, Iceland increased its other renewable energy usage (excluding hydroelectric) in 2010 based on its main energy type of petroleum and hydroelectric in 2000.

Third, when we focus on the renewable energy sources (hydroelectric, nuclear, and other renewable energy) contained in the main energy type in 2000 and 2010 (see Table 4), a small increase in the number of countries whose main energy types include one or more renewable energy sources from 36 to 39 is observed. The main energy types of most of these countries include hydroelectric (29 in 2000, 33 in 2010), followed by nuclear (11 in 2000, 10 in 2010), and an increase from 0 (in 2000) to 1 (in 2010) of countries whose main energy type contains other renewable resources occurred. Notably, 8 countries exist whose main energy types contain only renewable energy (i.e., hydroelectric). This phenomenon reveals that hydroelectric is the most common renewable energy and that some countries choose only hydroelectric as their main energy type, which is due to the superior hydroelectric energy technologies compared to nuclear and other renewable energy technologies.

Fourth, regarding the renewable energy sources in four types of countries (see Table 5), we find that type I, type III, and type IV branches have similar numbers of countries whose main energy types contain renewable energy and hydroelectric. However, type III and type IV branches have more countries whose main energy types contain nuclear energy, which implies that the development of nuclear energy requires superior technology and stronger economic strength. Note that 7 out of 8 countries whose main energy types contain only renewable energy (i.e., hydroelectric) are located in the type I and type II branches, which means that hydroelectric is relatively more stable and economical. Furthermore, the subordinate energy types of 8 countries contain petroleum, and these countries did not change their main energy types from 2000 to 2010.

Based on the evolution tree (Fig. 6) and the Markov chain (Fig. 7), we have arrived at the following conclusions.

First, the four types of countries exhibit distinct characteristics when clustered based on two factors that have a significant relationship with the energy consumption structure: GDP per capita and economic structure. Thus, countries with similar evolution trends (based on their energy consumption structure trends) are

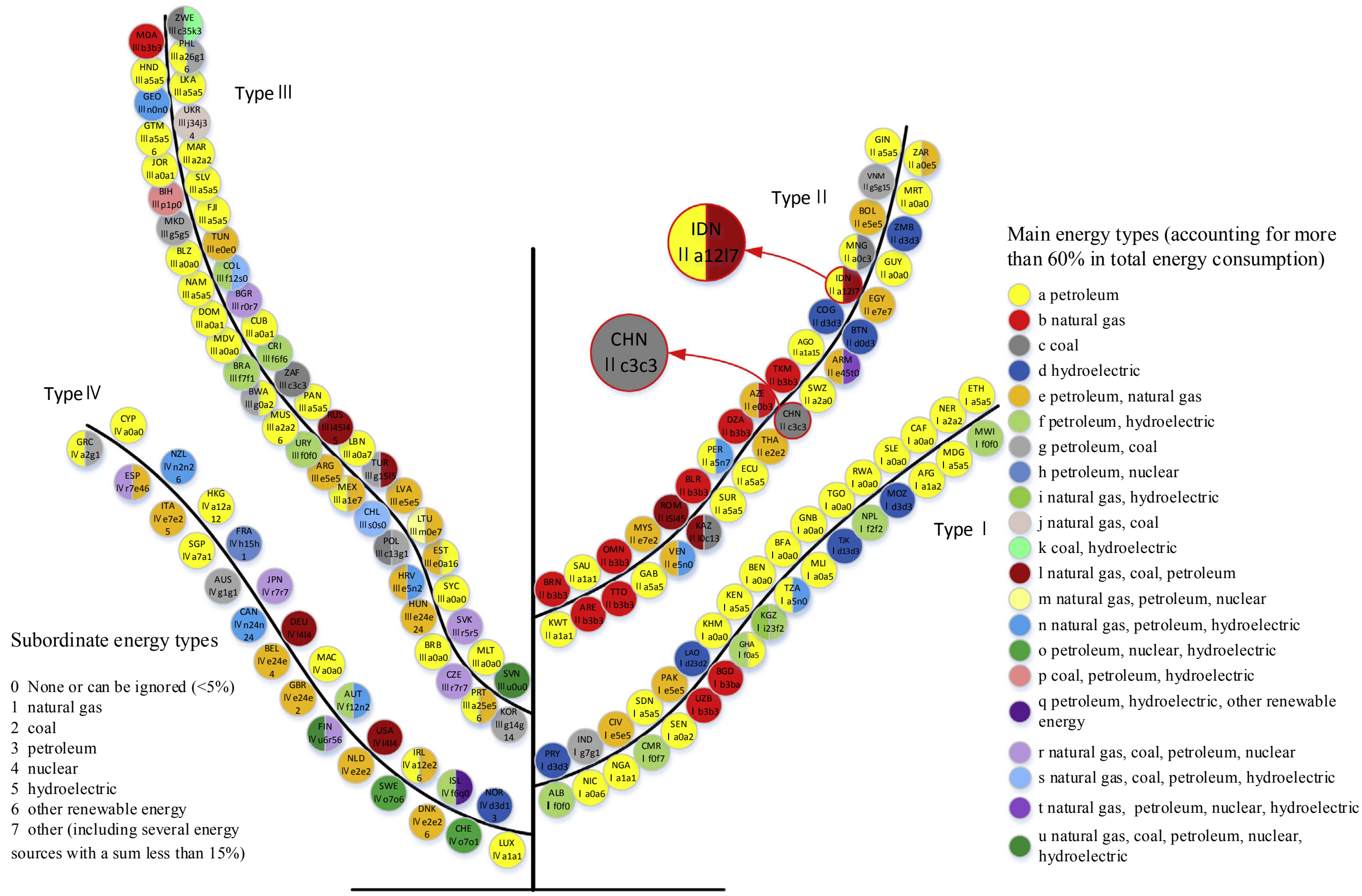


Fig. 6. Evolution tree of the energy consumption structure. Tree branches corresponding to country types are denoted by Roman numerals. Each leaf represents a country based on the three capital letters in the first line of the code. The pairwise combination of a letter and one or two digits in the second line of the code represents the energy consumption structure in 2000 and 2010. The color change in some leaves represents a change in the main energy type.

plotted along the same branch of the evolution tree.

Second, the connections between countries are revealed after they are projected onto the evolution tree. Two or more countries can be extracted to compare them with each other by identifying their location, color, and change in color. First, countries located in different branches have very different economic backgrounds. In contrast, if they are in the same branch and near each other, they share similar economic backgrounds and may follow similar evolution paths. Second, if they have the same color, then they have the same main energy type and similar energy consumption structures. In this case, they have a high possibility of following similar evolution paths. Moreover, if they have the same color change from 2000 to 2010, then they have already followed similar evolution paths and are likely to have the same evolution trend.

Third, countries in different branches of the evolution tree have different evolutionary paths. Countries in country type I have simple energy consumption structures that minimally change during the 10-year period. The mean GDP per capita of countries of this type is 701.3 dollars (constant 2005 USD), suggesting that poor economies are the primary hindrance to the improvement of energy consumption structures. In country type II, the energy consumption structures are also simple. Although some countries began to change their structures, most remained highly dependent on fossil fuels (see Fig. 7). The mean GDP per capita of these countries is 5744.3 dollars (constant 2005 USD), and secondary industry contributes a high proportion of their economic structures. We suggest that these countries improve their economies, optimize their industrial structures and promote the development of new energy technology. In country type III, the contributions of primary industry, secondary industry and tertiary industry are 6%, 28% and 66%, respectively. Therefore, these countries have relatively diverse energy consumption structures that changed considerably during the study period due to their industrial structures. In country type IV, countries use different types of energy according to their individual economic and consumption structures. Additionally, they actively develop new energy types, such as nuclear, hydroelectric and other renewable energy. For instance, Ireland changed its energy consumption structure from petroleum as the main energy type and natural gas and coal as subordinate energy types in 2000 to petroleum and natural gas as the main energy type and coal and other renewable energy as the subordinate energy types in 2010. The proportion of fossil-based energy decreased from 98% to 93%, and the proportion of clean energy-based electricity increased by 5%. In these countries, the contributions of primary industry, secondary industry and tertiary industry are 2%, 23% and 75%, respectively, and the mean GDP per capita is 40900.3 dollars (constant 2005 USD). This suggests that their diverse energy consumption structures are related to their optimal industrial structures, effective economic frameworks and advanced technological development.

5. Conclusions and discussion

In this paper, we built an evolution tree model to organize the

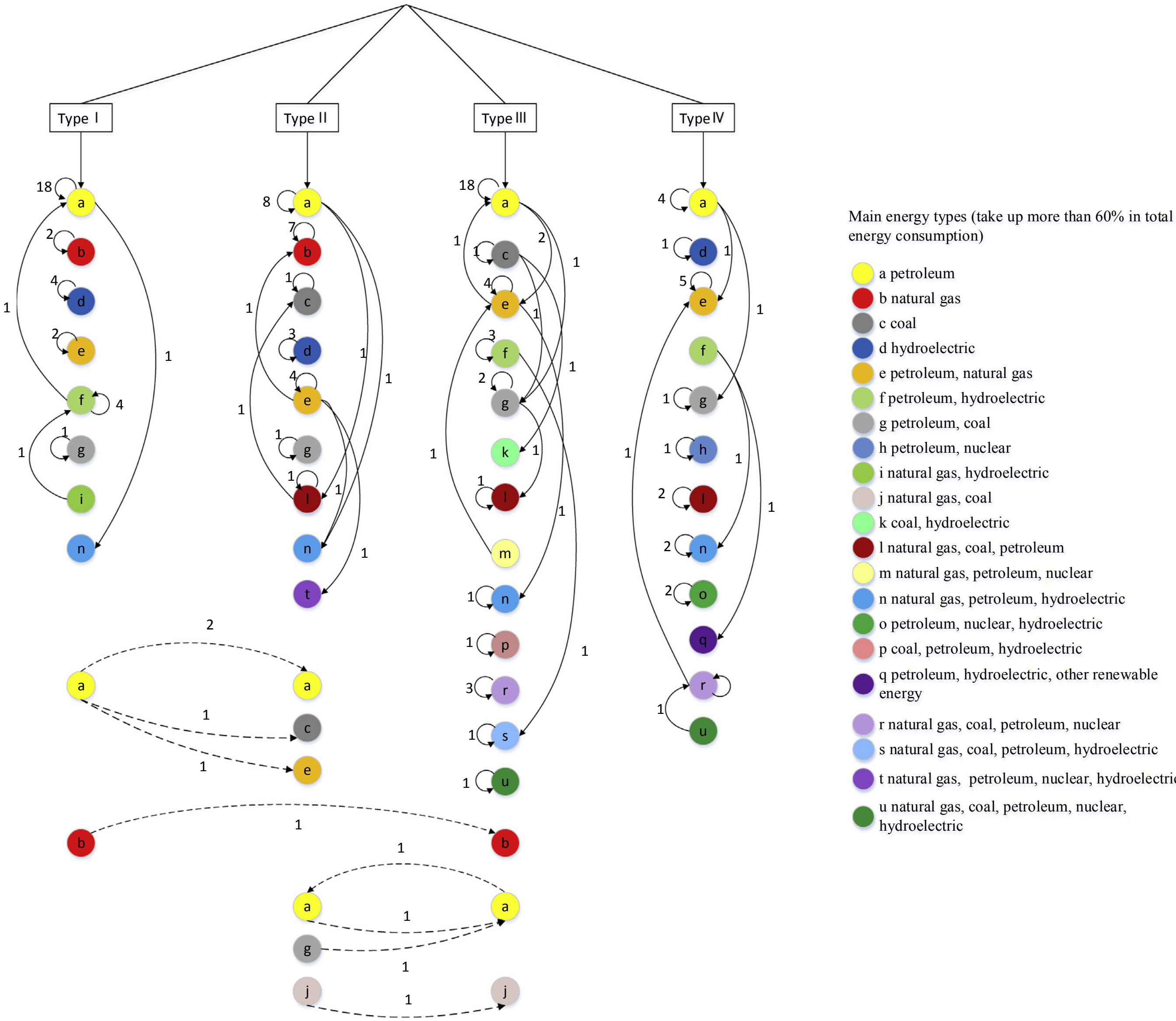


Fig. 7. Markov chain of the main energy types of countries. Arabic numerals indicate the number of countries in which a change in main energy type occurred. Roman numerals in the squares denote the country type (see Table 1). Letters in circles denote the main energy type (see Table 2). Arrows start at the main energy type in 2000 and point toward the corresponding main energy type in 2010. Dashed lines represent changes in country type.

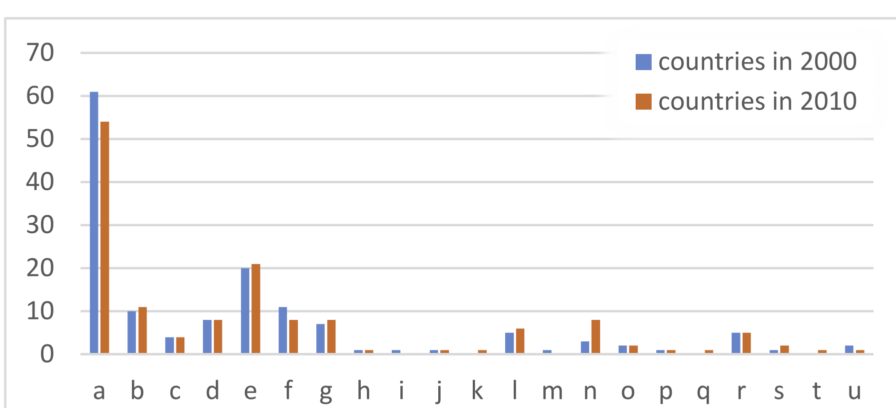


Fig. 8. Numbers of countries for every main energy type in 2000 and 2010.

Table 4
Renewable energy sources in 2000 and 2010.

	Number of countries in 2000	Number of countries in 2010
renewable energy contained in main energy type	36	39
hydroelectric contained in main energy type	29	33
nuclear contained in main energy type	11	10
other renewable energy contained in main energy type	0	1
main energy type is hydroelectric	8	8

Table 5
Renewable energy sources in four types of countries.

	Type I	Type II	Type III	Type IV
renewable energy contained in main energy type	12	6	15	14
hydroelectric contained in main energy type	12	6	11	10
nuclear contained in main energy type	0	1	5	7
other renewable energy contained in main energy type	0	0	0	1
main energy type is hydroelectric	4	3	0	1

energy consumption structures of 144 countries and regions for the years 2000 and 2010. The evolution tree provides a novel approach to observing and analyzing the global energy consumption structure. Based on the evolution tree, we established a Markov chain. Then, evolutionary trends were identified using both the evolution tree and the Markov chain. Based on the analysis above, we obtained the following major conclusions. First, countries that belong to the same type tend to have energy consumption structures that follow similar development paths. However, different types of countries and regions have different evolutionary trends. Second, the main energy types of most countries did not change during the research period analyzed in this paper. However, the countries that did change their main energy types generally became more diverse. Third, type IV countries, which are mainly developed countries, have the most diversified energy consumption structures. By contrast, the energy consumption structures of other types of countries and regions can be improved. Fourth, hydroelectric is the most common energy source among all renewable energy sources.

Based on the analysis and conclusions given above, we make the following suggestions by which countries can improve their energy consumption structures.

First, countries should know their positions in the global energy consumption structure. The evolution tree can be used to locate a country and assess the similarities to neighbors in the same branches. Moreover, users can analyze the differences between countries in different branches.

Second, countries can improve their energy consumption structures by understanding the issues that limit the improvement of these structures based on the experiences of other countries in the same branches. The evolution tree groups together countries with similar backgrounds. Based on our analysis, countries with similar energy consumption structures are plotted along the same branch and follow similar evolutionary paths. Therefore, these evolutionary trends provide a framework with which countries can establish energy structures that are more diverse and co-benefit the economy.

One specific limitation of this study should be noted. Both the GDP per capita and economic structure have a significant relationship with the energy consumption structure, and we cluster countries based on these two factors. However, resource endowment and the technological development level can also influence the energy consumption structure [1,30]. This study did not include these factors because of data limitations. To develop more convincing results, further studies must be conducted. All four factors considered (GDP per capita, economic structures, resource endowments and technological development levels) should be used to cluster countries. As such, countries of the same category would have more similar backgrounds, and the evolutionary trends exposed would be more precise.

Acknowledgments

This research was sponsored by the National Science-technology Support Plan Project of China (Grant nos. 2015BAJ02B00 and 2015BAJ02B03), the National Science and Technology Project (Grant nos. 2014FY210800) and the National Scientific Fund Project (Grant nos. 41701438).

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