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Assessing China's rural household energy sustainable development using improved grouped principal component method

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ABSTRACT

The purpose of this paper is to assess the status and progress of rural household energy sustainable development in China. A new composite indicator, rural energy sustainable development index (RESDI), is developed based on the improved grouped principal component analysis method (GPCA) which is the combination utilization of principal component analysis (PCA), factor analysis (FA), and entropy weight method. The improved grouped principal component analysis method keeps the advantages of principal component analysis and factor analysis. To capture the characters of rural energy sustainable development, ten indicators selected based on the criteria presented by OECD are designed to construct the RESDI. The main results are as follows. The RESDI increased from 0.185 in 1991 to 3.189 in 2012. However, the curve of RESDI can be divided into three phases: a slow increase stage between 1991 and 1996, a rapid decrease stage from 1997 to 1998, and a rapid increase stage between 1999 and 2012.

1. Introduction

Rural household energy consumption is of great importance as it directly relevant for residents' quality of life [1]. Nowadays, more and more rural households are becoming interested in using quality energy sources, that is to say the substitution of commercial energy for a non-commercial one. Along with the rapid rural economy development, total rural household commercial energy consumption in China rose from 64.28Mtce in 1991 to 107.99Mtce in 2012, representing an annual average growth rate of 2.5% [2]. The acceleration of environmental degradation with regard to ever-increasing energy use is posing threats to rural public health [3]. Providing sustainable energy for rural residents has been a priority for China government since the implication of new rural construction in 2005. Therefore, it is very necessary to assess the status and progress of rural household energy sustainability in China in formulating future policies.

So far, many existing literature have paid more attention to the development of energy sustainability indexes. More than 130 indicators were developed by the UN-CSD to describe the sustainable development index at the national level [4]. Kemmler and Spreng found that it was difficult to combine these large sets of indicators into a measurable and quantifiable sustainability index for assessing energy sustainable development [5]. Different sets of indicators have been utilized to assess energy sustainability [6]. OECD identified the criteria for selecting the indicators: (i) analytical soundness, (ii) measurability, (iii) country coverage, and (iv) ability to describe sustainability phenomenon of household energy in the rural context [7].

Some approaches were utilized to assess energy sustainability, such as principal component analysis, fuzzy set, and analytic hierarchy process, cluster analysis, factor analysis etc [8]. Based on the principal component analysis (PCA), Mainali et al. developed the energy sustainability index (ESI) to assess rural energy sustainability in five developing countries [9]. The neuro-fuzzy programming was utilized to perform a comparison between the different electricity power generation options for Jordan [10]. The analytic hierarchy process was used to explore the rural energy for sustainable development in different areas and periods [11]. However, there was no single commonly accepted method for assessing energy sustainability [12].

Based on different sets of indicators and different approaches, more general energy sustainability indexes were developed [13]. International Energy Agency developed the Energy Development Index (EDI) to assist policymakers in following progress made towards modern energy access provision [14]. The World Energy

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Trilemma presented an energy sustainability index ($ESI_{National}$) which covers indicators related to energy security, equity and environmental sustainability at national level [15]. Based on the fuzzy logic, the nuclear energy sustainability index was studied by Abouelnaga et al. [16]. The modeling of the energy system's sustainability index was studied by Afgan et al. [17].

China is a typical dual system structure. There exists significant imbalance in socio-economic development between urban and rural areas. Compared with urban areas, rural households have suffered long-term energy shortages [18]. The main fuel type for rural populations is conventional biomass energy. Thus, energy-related environmental problems are posing threats to rural public health. Therefore, rural energy issues in China have raised the concern of energy analysts and policy makers. Catania discussed the characteristics of a rural society, outlined the relationship of rural energy supply and demand management [19]. Common factors that influence Chinese rural household energy consumption and major demand characteristics of well-off rural areas were analyzed on the basis of survey data by Wang and Feng [20]. Affecting factors and standard of rural household energy consumption in China were studied by Wang and Feng [21]. Zhou et al. thoroughly analyze household energy consumption in terms of energy sources and energy end-uses in villages of Huantai County from 1989 to 2005 [22]. Zhang and Guo utilized the LMDI method to identify the contributing role of different factors affecting the change of rural residential energy consumption in China [23]. The development potential of biomass and other renewable resources has also been studied by Li et al. and Byrne et al. [24,25].

So far many studies have focused on China's rural energy consumption and its energy-related CO_2 emission. To the best of our knowledge, only several papers utilized the systematical method to study rural energy development issues. Zhou et al. explored the sustainable development of rural household energy in northern China [26]. The change in spatial distribution and influencing factors of rural energy consumption in 29 provinces of China was analyzed by using factor analysis, cluster analysis, and regression analysis [27]. Nevertheless, the rural energy sustainability development in China has not evaluated by systematical method. This paper aims at completing this task. Thus by combining principal component analysis, factor analysis (FA), and entropy weight method, this paper develops a new composite indicator, rural energy sustainable development index (RESDI), which is used to assess the status and progress of rural household energy sustainability in China.

The remainder of paper is organized as follows: The theoretical framework of the improved grouped principal component method is presented in Section 2. Section 3 discusses the selected indicators. Section 4 presents the main results. The discussion is presented in Section 5. The conclusions are summarized in Section 6.

2. Theoretical framework

Since the 1990s, some approaches have been used to assess the energy sustainability, such as Ecological Footprint, Pressure-State-Response model, Barometer of Sustainability, Sustainability Assessment by Fuzzy Evaluation, Environmental Sustainability Index, Multi Criteria and Fuzzy Logic, etc. The common characteristic of these approaches is to depict progress in energy sustainable development based on a number of indicators [8]. The purpose of this paper is to construct a new composite indicator, rural energy sustainable development index (RESDI). To deal with the simultaneous treatment of a series of variables, the use of a multivariate method is required. The construction of the RESDI is based on the use of some techniques, such as Principal Component Analysis, Factor Analysis, Entropy Weight Method.

The PCA, a multivariate technique, is frequently used to construct sustainable development indecator. The PCA is a mathematical method by which the possibly correlated variables (indicators) are transformed into uncorrelated principal components using orthogonal transformation of a correlation matrix. The PCA can compress the dimensionality of a large number of interrelated data sets without much loss of information. The detailed description of the PCA method can be referred to the paper by Li et al. [13]. However, the PCA also has some limitations. One is representation of the first principal component which is depended on the correlation between the variables indicators. The other is the positive and negative coefficients of each indicator variables in principal component, which may differ from the actual meaning of variables.

FA consists of a number of statistical techniques the aim of which is to simplify the complex sets of data. The advantage of the factor analysis is that factor variables can be more interpretable by rotating, which can help classify the evaluation indicators. The detailed description of the factor analysis method can be referred to the paper by Li et al. [27]. The combination utilization of PCA and FA can handle the limitation of PCA. Thus, by combining PCA, FA, and entropy weight method, this paper develops an improved grouped principal component method, which is used to calculate RESDI.

Suppose there are n samples, and each sample has p indicators (variables). Thus each indicator can be expressed as$X_j = (X_{1j}, X_{2j}, \ldots, X_{nj})$, $j = 1,2,\ldots,p$. All observations consist of a matrix$X = (X_{ij})_{n\times p}$, $i = 1,2,\ldots,n, j = 1,2,\ldots,p$. Since these indicators are of different measurement units, direct aggregation is not possible. The specific steps of the improved grouped principal component method are as follows.

Step 1. Each selected original indicator is normalized using the following formula (1).

$$z_{ij} = \frac{X_{ij} - Min(X_j)}{Max(X_{ij}) - Min(X_{ij})}. \tag{1}$$

The standardized matrix can be expressed as $Z = (z_{ij})_{n\times p}$.

Step 2. Calculating the correlation matrix ($R = (r_{ij})_{p\times p}$) of the standardized matrix ($Z = (z_{ij})_{n\times p}$).

Step 3. Calculating the eigen values ($\lambda_1 \ge \lambda_2 \ge \cdots \ge \lambda_p \ge 0$) and eigenvectors ($L_1, L_2, \ldots, L_p$) of the correlation matrix. According to the rule of PCA ($\sum_{i=1}^{m}\lambda_i / \sum_{i=1}^{p}\lambda_i \ge 85\%$), m principal components are determined.

Step 4. Using the FC method, the rotating factor loading matrix of each factor is received. Because the factor rotation makes each variable has the largest load on one factor, the standardized indicators are divided into m groups depend on the largest load.

Step 5. Based on the PCA method, the principal components of the k th group are extracted, denoted by PC_l^k, $k = 1,2,\ldots,m$, $l = 1,2,\ldots,k_m$. Here, k_m is the number of the principal components of the k th group.

Step 6. All extracted principal components in step 5 compose a new matrix ($S = (s_{ij})_{n\times t} = (S_1, S_2, \ldots, S_t)$), where t is the number of all extracted principal components.

Step 7. Using the entropy weight method, the weight of each principal component of S is calculated. The information entropy of the j th principal component of S, denoted by E_j, can be calculated by the following formula (2).

$$E_j = -(\ln n)^{-1} \sum_{i=1}^{n} p_{ij} \ln p_{ij} \tag{2}$$

Where, $p_{ij} = s_{ij} / \sum_{i=1}^{n} s_{ij}$. If $p_{ij} = 0$, then this paper defines $\lim_{p_{ij}\to 0} p_{ij} \ln p_{ij} = 0$. The weight of each principal component can be