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Evaluating clean energy alternatives for Jiangsu, China: An improved multi-criteria decision making method

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ABSTRACT

Promoting the utilization of clean energy has been identified as one potential solution to addressing environmental pollution and achieving sustainable development in many countries around the world. Evaluating clean energy alternatives includes a requirement to balance multiple conflict criteria, including technology, environment, economy and society, all of which are incommensurate and inter-dependent. Traditional MCDM (multi-criteria decision making) methods, such as the weighted average method, often fail to aggregate such criteria consistently. In this paper, an improved MCDM method based on fuzzy measure and integral is developed and applied to evaluate four primary clean energy options for Jiangsu Province, China. The results confirm that the preferred clean energy option for Jiangsu is solar photovoltaic, followed by wind, biomass and finally nuclear. A sensitivity analysis is also conducted to evaluate the values of clean energy resources for Jiangsu. The ordered weighted average method is also applied to compare the method mentioned above in our empirical study. The results show that the improved MCDM method provides higher discrimination between alternative clean energy alternatives.

1. Introduction

Over the past decade, the world's total primary energy consumption increased from 402 quadrillion Btu in 2001, to 510 quadrillion Btu in 2010 [1]. Although different fossil energy resources have different costs and their CO_2 emissions also vary [2], the majority (approximately 87%) of global energy consumption arises from the processing and usage of fossil fuel; and this process also produces greenhouse gases and other airborne pollutants.

Growing international concerns about the impact of fossil fuel consumption on the global climate and environment has prompted many countries to focus on the development and utilization of emerging clean energy sources.[1]

Selecting an appropriate clean energy resource must be specific to a particular jurisdiction. The selection of clean energy resource alternatives also involves complex trade-offs. For example, wind energy may be highly efficient but very expensive, while nuclear energy may have a low operational cost but a potentially high risk. Selecting the appropriate clean energy resources for a given jurisdiction is important, as the right decision will also provide opportunities to create new economic markets and employment possibilities. More importantly, choosing the most appropriate clean energy resource will also act as a catalyst for reforming the structure of energy use and (or) the local economy. However, the use of clean energy resources also presents a number of persistent technical limitations and relatively high production costs, at least in the near future. In this case, the selection of clean energy resource alternatives has attracted attention from both researchers and practitioners.

Determining the preferred clean energy resources is essentially a typical MCDM (multi-criteria decision making) problem [4]. In addition, MCDM techniques have been widely applied as a means to solve energy resource selection problems under various decision

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[1] Hydropower, Wind power, Solar power, Biomass power and Nuclear power are considered to be clean energy resources in China [3].

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making contexts. For example, a review of previously published studies on sustainable energy planning identified that Multi-Objective Optimization (29%), the AHP (analytic hierarchy process) (20%), ELECTRE (elimination and choice expressing reality) (15%) and the PROMETHEE (preference ranking organization method for enrichment of evaluations) (10%), are the principal methods used to address this problem [5].

One common feature when attempting to solve the above problem is that most MCDM methods used to evaluate energy resource alternatives assume that the criteria are independent of each other. Due to this assumption, it is particularly difficult to build a comprehensive set of independent criteria for large evaluation systems (e.g. a clean energy resources evaluation). The interdependence issue remains a significant barrier to the effective application of MCDM in this context [6]. For MCDM problems with interactive criteria, fuzzy measures have recently been proposed as a means to weight the criteria and their coalitions, followed by the use of a fuzzy integral to aggregate partial evaluations [7]. As a form of non-additive measure, fuzzy measures represent a generalization of classical measures. They are derived by replacing the additive property with a weaker monotonicity [8]. Marichal [9] demonstrated that all forms of interaction between criteria (including the preferential interaction between expert opinions) can be modeled effectively by using fuzzy measures.

In previous studies, there have been extensive studies of fuzzy measures and fuzzy integrals, which mainly focused on theoretical development [10–12]. The practical application of fuzzy measure methods to genuine MCDM scenarios is far more limited, especially in the context of clean energy resource evaluation. This paucity of actual application is primarily due to the complexity of determining effective fuzzy measures. To address this complex issue without a large amount of expert opinion, λ fuzzy measure [13] has been proposed. In particular, λ fuzzy measure has gained great popularity because of its potential for use in a broad range of applications, and because it is easy to calculate and simple to interpret [14].

This paper aims to assess clean energy resource alternatives for the Jiangsu Province of China, using the λ fuzzy measure to weight interactive criteria and their coalitions. The rest of this paper is organized as follows. The clean energy options for Jiangsu are discussed in the context of actual background information in Section 2. Section 3 presents the evaluation methodology, including the critical techniques and key processes. Section 4 constructs and assesses the evaluation criteria for clean energy resource alternatives specific to Jiangsu Province. The clean energy resource alternatives are also evaluated by using the fuzzy measure and integral method. Section 5 conducts the sensitivity analysis. Section 6 discusses the results of the evaluation and sensitivity analysis. Section 7 presents the conclusions.

2. Background information

Since the initiation of economic reforms in 1990, Jiangsu has become one of the most developed provinces in China. With rapid economic growth and accelerated urbanization, a resources shortage and environmental pollution have become critical issues to the development of Jiangsu. Fig. 1 shows Jiangsu's energy importation and discharges of industrial gas from 2002 to 2012.

In order to ensure that the region's resource supply, environmental quality and social benefits keep pace with the rapid economic development and on-going urbanization, reducing the impact of energy supply through the adoption of clean energy resources is a critical factor for the region's sustainable development [3,15]. The potential clean energy resources that may be used by Jiangsu may include solar PV (photovoltaic), wind, water, biomass, geothermal and nuclear. However, the use of water resources and geothermal energy are not considered viable alternatives. Geothermal sources have low temperatures which makes them suitable for heating but not for power generation. Water is not considered to be a solution in Jiangsu's clean energy plan, because most water resources are located in the southwestern regions of China [3]. In addition, the majority of the water resources in Jiangsu Province has already been developed [16]. Four other types of clean energy (solar PV, wind, biomass, and nuclear energy) will be considered as available clean energy resource alternatives in this study. Solar power is generally the most robust with 83 TWh exploitable potential per annum in Jiangsu [17].

Jiangsu's total wind energy potential is about 30.300 MW [18]. According to the China Yearbook of New Energy and Sustainable Energy 2012, the accumulated installed capacity of wind energy generation was approximately 2460 Kilowatt. In addition, Jiangsu has abundant wind resources located [19] along the coast. Copious biomass resources are also available in Jiangsu Province, since 40 million tons of straw and 10 million tons of livestock excrement produced annually [20]. Based on the Jiangsu Statistical Yearbook in 2013, there is currently only a single nuclear power plant operating in Jiangsu Province, with an installed capacity of 2 GW. This facility delivers 16.241 TWh of electricity annually. In this case, solar PV, biomass, wind and nuclear are taken into account by the Jiangsu government as a means to improve the region's sustainable development.

The essential and urgent question for Jiangsu Province remains, however, how to determine the priority (in terms of preference) of those clean energy resources so that Jiangsu can design and implement the most appropriate clean energy strategies? Because clean energy is not considered to be just a solution for energy shortage, but also for mitigating climate change and environmental pollution [21], technological, environmental and social factors must be taken into account, as well as economic factors [22]. The total sustainability values of clean energy resources must be calculated based on all related criteria, in order to assess the clean energy resources comprehensively [22]. Clean energy resources can then be ranked according to those values. Because many criteria are taken into account, MCDM is a suitable tool for analyzing clean energy fields. Fruitful studies have been conducted analyzing clean energy resources using MCDM [21–23]. For instance, PROMETHEE [24], AHP [25–28], the VIKOR method [29], OWA (ordered weighted averaging) [30] and the TOPSIS (technique for order preference by similarity to an ideal solution) [31] have been widely utilized in the field of clean energy resources. Until now, in most of the published studies, the evaluation criteria of clean energy resource alternatives have been hypothesized as independent from each other [28]. In fact, there are inevitable interaction between these criteria [6,24,32].

3. Methodology

In the context of a clean energy resource evaluation, interactions may exist between different criteria. In order to handle criteria with complex interactions, λ fuzzy measures and a Choquet integral are used in the evaluation method to weight the criteria and aggregate their weights and values, respectively. The hybrids method of EWM (entropy weight method), Shapley Values and Marichal Entropy [33] was proposed to determine the fuzzy measures, followed by the Choquet integral, which was adopted to determine the synthetic values for each clean energy resource.

3.1. Concepts of λ fuzzy measure and Choquet integral

Let $C = \{c_1, c_2, \ldots, c_m\}$ denote a space of states and $X = \{x_1, x_2, \ldots, x_n\}$ be a space of alternative states (also known as an evaluation