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Modelling policy decision of sustainable energy strategies for Nanjing city: A fuzzy integral approach

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ABSTRACT

Regional energy plans play a significant role in promoting the sustainable development of different regions in China. Most regions of China have formulated their energy plans. Selecting a reasonable sustainable energy plan is complex and involves a number of interactive criteria (e.g. technology, environment, economy and society). The traditional decision analysis methods, such as analytical hierarchy process and cost-benefit analysis, are not sufficient to integrate all the criteria with mutual interaction. On the contrary, the fuzzy integral methods provide a tool to resolve this problem and offer valid decision support since it is more appropriate to assemble and handle decision problems with interaction. This paper presents λ fuzzy measure and fuzzy integral method for selecting the sustainable energy plan of Nanjing city in China. A set of energy planning alternatives are determined upon the implementation of installations of sustainable energy sources in Nanjing and assessed against economic, technological, social and environmental criteria.

1. Introduction

According to mid-long term development plan of China, 15% of electricity should be generated from renewable energy by the year 2020. To achieve this goal, sustainable energy plans have been carried out in most regions of China. It is observed that most of the energy plans are very similar and moreover some sustainable energy projects were overlapped in different places, which is not in accordance with the rule of sustainable development. As the capital of Jiangsu province, Nanjing has over 7.4 million residents and 6598 square kilometres municipal district. It is an important modern manufacturing base, and its pillar industries include high-tech electronic information, auto industry, petrochemical industry and iron and steel industry. Most of the pillar industries in Nanjing are highly energy-consuming. In 2011, 0.842 ton Standard coal was consumed for producing ten thousands RMB GDP. With its positive economic development capacity, energy demand will challenge the existing energy system of Nanjing. Developing sustainable energy sources will help Nanjing to realize its sustainable development and achieve the goal of 2020.

According to the twelfth five-year plan of Nanjing city, the sustainable development can be realized through three possible approaches. The first approach is that the city should adjust the structure of industry and production, which requires decreasing the number of industry with high energy consumption and to increase those with less energy-intensive. The second approach is to improve the energy efficiency through the introduction of modern technology. And the third approach is to develop other new sustainable energy sources. It is believed that the first two approaches can hardly decrease energy consumption in Nanjing in the near future because they cannot be realized in a short time span. Despite of the government's efforts focused on the first two approaches the energy consumption in Nanjing could not be reduced. This is evident from the figures that the energy consumption in the year 2011 increased by 2.45 times as compared to the year 2007 and the electricity consumption in the same period doubled. So developing new energy source is the only feasible way to realize Nanjing's sustainable development. New sustainable energy includes renewable energy and other energy sources. Nanjing has enormous potential for developing various sustainable energy technologies, such as solar energy, geothermal energy. However, sustainable energy should satisfy technical and cost limits and must contribute to environment protection and social development [1–3]. So, when evaluating the feasibility of sustainable energy plans, multiple criteria should be taken into consideration.

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This research aims to assess various sustainable energy plans and propose the suitable energy development strategy for Nanjing. There are many sophisticated analytical methods used to seek optimal solutions for decision-making problems of sustainable energy plan. Such as PROMETHEE [2,4], The analytic hierarchy process (AHP) [1,5–7], VIKOR method [8], ordered weighted averaging (OWA) [9] and TOPSIS [10]. Since the judgements of policy makers sometimes have the feature of ambiguity and uncertainty, researchers tend to analyse the problems with fuzzy set theory [1,7] and linguistic variable [9]. Furthermore, in most of the published research the decision making criteria are hypothesized as independent from each other [1–4,7]. While in reality independent criteria can hardly be formulated [2,3]. For instance, efficiency, reliability and cost are usually selected as criteria in order to evaluate the pros and cons of various sustainable energy plans. But to certain extend, technical efficiency is correlated with reliability and cost [3] and hence cannot be treated as independent from them. As a kind of non-additive measure, fuzzy measures represent a generalization of classical measures. They are obtained by replacing the additive property of classical measures with a weaker requirement of monotonicity [11]. Based on fuzzy measures, fuzzy integral acting as the aggregate tools was proposed. To date, lot of theoretical research have been done in the field of fuzzy measures and integrals [12–15]; their application research has been blooming [16–20]. Solving multi-criteria evaluation problems with interdependence, fuzzy measures can be used for weighting the criterion and their combination, and fuzzy integral can be used for aggregating partial evaluations [12,13]. The advantage of using the fuzzy integral within a multi-criteria method is its unique behavioural property [11]. And λ fuzzy measure is a special kind of fuzzy measure widely used because of its convenience in computations [17]. Therefore, λ fuzzy measures and fuzzy integral can be used to aid in decision-making of sustainable energy planning for Nanjing. The organization of this paper is as follows. The general outline of sustainable energy strategies decision-making model is shown in Section 2. Section 3 builds up the criteria and briefly illustrates the interaction between the criteria to evaluate the sustainable energy plans for Nanjing. The λ fuzzy measure of criteria and λ values are calculated based on the concept of Marichal entropy in Section 4. Based on Nanjing's background and related literature, various sustainable energy plans are constructed and evaluated with fuzzy integral in Section 5. Finally, Section 6 presents the conclusion.

2. The general outline of sustainable energy strategies decision-making model

We introduce the notions of a space of states $A = \{a_1, a_2, \ldots, a_n\}$, and a decision space (a space of alternatives) $X = \{x_1, x_2, \ldots, x_m\}$. We consider a decision model wherein m alternatives $x_1, x_2, \ldots, x_m \in X$ act as city's plans about sustainable energy strategies. The plans should influence n states $a_1, a_2, \ldots, a_n \in A$, which are identified with n facets typical of the city we should consider.

Let us further associate with each a_j ($j = 1, \ldots, n$) and their coalitions, a non negative number will be applied to indicate its power or importance in decision making. Considering the interaction between criteria and the advantage of computation, λ fuzzy measure is applied to model the importance of criterion a_j ($j = 1, \ldots, n$) and their coalitions. Let $P(A)$ denote the power set of A, the definition of λ fuzzy measure is given as follows.

Definition 1. [17] λ fuzzy measure on the set A of criteria is a set function g_λ: $P(A) \to [0,1]$ satisfying the following properties:

1. $g_\lambda(\varphi) = 0$, $g_\lambda(A) = 1$ (boundary conditions);
2. For any $R, S \in P(A)$, if $R \subset S$, then $g_\lambda(R) \le g_\lambda(S)$ (monotonicity);
3. $g_\lambda(M \cup N) = g_\lambda(M) + g_\lambda(N) + \lambda g_\lambda(M)\, g_\lambda(N)$ where $-1 < \lambda < \infty$ for all $M, N \in P(X)$ and $M \cap N = \varphi$.

Now, considering a pair $M, N \in P(A)$ $(M \cap N = \varphi)$ of criteria, the difference $a(M, N) = g_\lambda(M, N) - g_\lambda(M) - g_\lambda(N)$ seems to reflect the degree of interaction between M and N. This difference is zero if M and N are independent. It is positive if there is a synergy effect between M and N and negative if they are redundant. Here again, the interaction between M and N should depend on the coefficients λ.

Because there exist interaction between the decision-making criteria, the overall contribution of a criterion $a_i \in A$ in the whole decision-making process is not solely determined by the value $g_\lambda(a_i)$, but also by all $g_\lambda(S)$ where $a_i \in S$. The importance index or Shapley value of criterion $a_i \in A$ with respect to g_λ is defined by:

Definition 2. [21] The importance index or Shapley value of criterion a_i with respect to g_λ is defined by:

$$s(a_i) = \sum_{k=0}^{n-1} \frac{(n-k-1)!k!}{n!} \sum_{T \subseteq A/a_i, |T| = k} \left(g_\lambda(T \cup a_i) - g_\lambda(T)\right) \tag{1}$$

According to the definition of Shapley value, the following equation can be obtained:

$$s(a_1) + s(a_2) + \ldots + s(a_n) = 1 \tag{2}$$

Consider a given object f, whose corresponding scores on each criterion are numerical values as $f(a_1), \ldots f(a_n)$. To compare different objects, we need to obtain an overall score from $f(a_1), \ldots f(a_n)$. Choquet integral is one of the most popular aggregation operators when interaction exists between criteria.

Definition 3. [22] For a multi-criteria evaluation problem with criteria set A, g_λ is the λ fuzzy measure defined on A. And then Choquet integral is defined on λ fuzzy measure as f: $A \to IR^+$

$$(C)\int f \mathrm{d}\mu = \sum_{i=1}^{n} \left(f\left(a_{(i)}\right) - f\left(a_{(i-1)}\right)\right) g_\lambda\left(A_{(i)}\right) \tag{3}$$

Among which (i) is the transfer of vector $f(a_{(i)})$, and $0 \le f(a_{(1)}) \le \ldots \le f(a_{(n)})$, $A_{(i)} = \{a_{(i)}, \ldots, a_{(n)}\}$, also $g_\lambda(A_{(0)}) = 0$, $f(a_{(0)}) = 0$.

The Choquet integral is a generalization of the concept of expected value, and models based on it are generalizations of the weighted average model.

3. Evaluation criteria and their interaction

3.1. Evaluation criteria

We directly employ the criteria mostly cited in selection of sustainable energy plans and listed in Ref. [3]. According to reference [3], 25 evaluation criteria are often applied to assess the sustainable energy plan. And total reference number of these criteria is 199 [3]. So, the average reference number of each criterion is 7.9 (=199/25). If the criterion's total reference number is less than 7.9, we abandon it in this research except the criteria of 'social benefit'. Since Nanjing is a developing region, social benefit is very helpful to realize its sustainable development. In order to reduce the total number of the assessment criteria, the term 'GHG emissions reduction' is used to combine NO_x emission, CO_2 emission and SO_2 emission together. The total reference number of GHG emissions reduction is equal to the sum of the total reference number of NO_x emission, CO_2 emission and SO_2 emission. So the total reference number of GHG emissions reduction is 41(=12 + 21 + 8) according to [3]. The sum of total reference number of the siblings is their corresponding father's total reference number. The criteria for evaluating Nanjing sustainable energy plan is shown in Table 1.