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Research Article

A Novel Evaluation Model for Hybrid Power System Based on Vague Set and Dempster-Shafer Evidence Theory

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Because clean energy and traditional energy have different advantages and disadvantages, it is of great significance to evaluate comprehensive benefits for hybrid power systems. Based on thorough analysis of important characters on hybrid power systems, an index system including security, economic benefit, environmental benefit, and social benefit is established in this paper. Due to advantages of processing abundant uncertain and fuzzy information, vague set is used to determine the decision matrix. Convert vague decision matrix to real one by vague combination ruleand determine uncertain degrees of different indexes by grey incidence analysis, then the mass functions of different comment set in different indexes are obtained. Information can be fused in accordance with Dempster-Shafer (D-S) combination rule and the evaluation result is got by vague set and D-S evidence theory. A simulation of hybrid power system including thermal power, wind power, and photovoltaic power in China is provided to demonstrate the effectiveness and potential of the proposed design scheme. It can be clearly seen that the uncertainties in decision making can be dramatically decreased compared with existing methods in the literature. The actual implementation results illustrate that the proposed index system and evaluation model based on vague set and D-S evidence theory are effective and practical to evaluate comprehensive benefit of hybrid power system.

1. Introduction

At present, climate warming and environmental pollution are becoming increasingly prominent, which poses a serious threat to sustainable development of human society. Developing clean energies, such as wind power and photovoltaic power, is widely accepted common choice of the world [1–5]. Clean energy and traditional energy have their own different characteristics. As to thermal power, it has advantages of low cost and stable power, but generally causes serious pollution, especially carbon dioxide, whereas clean energy power has the disadvantages of high cost and instability, but is highly environmental friendly [6–9]. A power system usually includes thermal power, wind power, and photovoltaic power. Because of different techniques and economic influences, it is of practical significance to choose scientific, comprehensive, and reasonable indexes, and methods to evaluate comprehensive benefit of hybrid power system.

Numerous factors should be considered to evaluate the comprehensive benefit of hybrid power system, such as technique security, influence to environment, and economy [10]. Literatures [11, 12] have analyzed economic aspect of power system; security and technique aspect are considered in [13, 14]; the work in [15, 16] evaluated environmental influence of different energies. However, only a few attempts have been made on social benefit of power system, let alone comprehensive benefit including social and environmental aspects of hybrid power system.

The input indexes are critical for comprehensive evaluation and are often complex, which involves production, scheduling, dispatch, marketing, planning, and finance as well as many other aspects [17]. Because of ambiguity of characters of evaluation indexes, it is suitable for information fusion technique to evaluate comprehensive benefit of hybrid power system which allows representation of both imprecision and uncertainty [18, 19]. Information fusion technique includes several kinds of methods, such as Kalman filtering, Bayesian estimation, and D-S evidence theory. Because Kalman filtering is depending on the initial state estimation, and by measuring the noise influence such as large faults, estimate process covariance easily appears morbid, leading to filter positioning results are not stable. Bayesian is a kind of commonly used method for static environment fusion in sensor lower information, suitable for normal distribution measuring result or additive Gaussian noise system. D-S evidence theory tackles the prior probability issue by keeping track of an explicit probabilistic measure of a possible lack of information. It is suitable take into account the disparity between knowledge types [20] because it is able to provide a federative framework [21] and it combines cumulative evidence for changing prior opinions in the light of new evidence [22]. Literature [23] proposed the combined fuzzy logic/D-S evidence theory method. Although Jones et al. [24] noted that it is necessary to ensure the validity of basic probability assignment, they did not give a method to do so. Vague set is proposed to solve the problem in this paper.

Due to advantages of vague set processing abundant uncertain and fuzzy information, it is chosen to determine basic decision matrix of evaluation model [25–30]. Combining vague set with D-S evidence theory, a novel evaluation algorithm is established and applied into the comprehensive benefit evaluation of hybrid power system.

The paper is organized as follows. Section 2 proposes a systematic evaluation index system according to characters of hybrid power system. A comprehensive evaluation model based on vague set and D-S evidence theory is given in Section 3. A simulation of hybrid power system including thermal power, wind power, and photovoltaic power in China is proposed, and comparison between the proposed evaluation model with some existing works is analyzed in Section 4. The paper is conducted in Section 5.

2. Evaluation Index System

Comprehensive benefit evaluation of hybrid power generation should not only include economic benefit, but also its impact on the environment, namely, environmental benefit.

Due to the public service property of electric power, it is necessary to consider social benefit; meanwhile, because of instable clean energy generation, it is needed to consider the security of the power system. This paper establishes comprehensive benefit evaluation index system of hybrid power system from the four aspects of economic benefit, environmental benefit, social benefit, and security.

2.1. Economic Benefit

Economic benefit is the most important aspect of comprehensive benefit evaluation. It is mainly composed of the four aspects of profitability capability, solvency capability, operational capability, and development capacity.

Profitability refers to the ability to profit in a certain period. Profitability capability is determined by comprehensive consideration of gross profit margin, net profit margin, ratio of profits to cost, and return on total assets. Solvency capability refers to the ability to repay due debts which be assessed in terms of current ratio, quick ratio, asset-liability ratio, and interest coverage ratio. Operational capacity refers to enterprise's ability to make profits using existing assets. This paper mainly assesses the operational capability through current asset turnover, fixed asset turnover, and total asset turnover. Development capacity refers to the potential ability to expand scale and grow strength in the coming years which can be accessed through profit growth, sale growth, and total asset growth.

2.2. Environmental Benefit

Environmental benefit refers to the influence on living environment, which can be divided into positive benefit, negative benefit, direct benefit, and indirect benefit. Fundamentally speaking, environmental benefit is the basis of economic benefit and social benefit. Environmental benefit is a qualitative index. Comprehensively considering circumstances of hybrid power system, this paper evaluates environmental benefit from the two aspects of saving natural resources and reducing scraps.

2.3. Social Benefit

Social benefit refers to the good consequences and implications for community and society, also known as external and indirect economic benefit, mainly in forms of public reflection and social assessment system. Social benefit is a qualitative indicator. Comprehensively considering the specific circumstances of hybrid power system, this paper establishes social benefit evaluation index system from the three aspects of pulling gross domestic product, improving people's living standard and promoting social employment.

2.4. Security

Security occupies a basic position in comprehensive benefit evaluation of power grid. Combined with exiting researches and characters of hybrid power system, this paper selects four indexes to evaluate security, including integrated voltage qualification rate, grid frequency qualification rate, average loading rate of provincial grid, and power supply reliability rate.

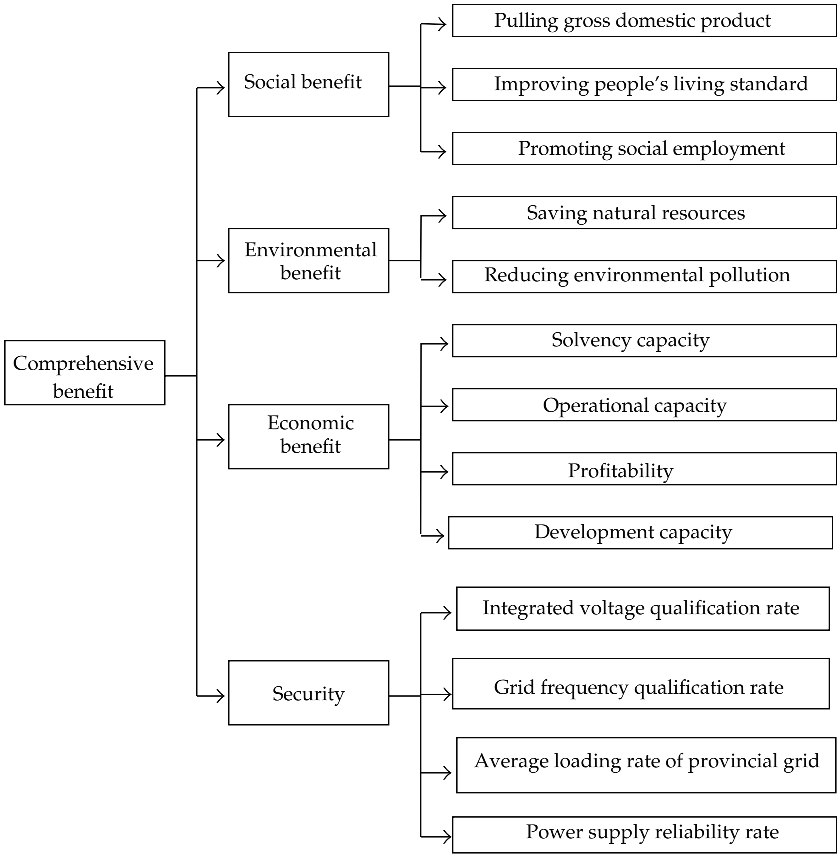

Figure 1: Comprehensive evaluation index system.

Above all, the comprehensive benefit evaluation index system of hybrid power system is shown in Figure 1.

3. Model Establishment

3.1. Decision Matrix Based on Vague Set

Vague set proposed by Gau and Buehrer [31] is a generalized form of fuzzy set. Vague set has been successfully applied in the field of fuzzy control, decision analysis and expert systems, and has achieved better results than the traditional fuzzy set theory [32–34].

Set U the universe of discourse, with a generic element u. A vague set A is characterized by a truth-membership function t_A and a false-membership function f_A, where $t_A(u)$ is a lower bound on the grade of membership of u, derived from the evidence rising for u; $f_A(u)$ is a lower bound on the negation of u, derived from the evidence against u; $0 \le t_A(u) + f_A(u) \le 1$. The grade of membership of u in vague set A is bound to a subinterval $[t_A(u), 1 - f_A(u)]$ of $[0, 1]$. The vague value $[t_A(u), 1 - f_A(u)]$ indicates that the exact grade of membership $\mu_A(u)$ of u maybe unknown, but it is bound by $t_A(u) \le \mu_A(u) \le 1 - f_A(u)$, where $0 \le t_A(u) + f_A(u) \le 1$.

When the universe of discourse U is discrete, a vague set A can be written as

$$A = \sum_{i=1}^{n} \frac{\left[t_A(u_i), 1 - f_A(u_i)\right]}{u_i}, \quad u_i \in U. \tag{3.1}$$

When the universe of discourse U is continuous, a vague set A can be written as

$$A = \frac{\int_U \left[t_A(u_i), 1 - f_A(u_i)\right]}{u_i du_i}, \quad u_i \in U. \tag{3.2}$$

The steps of determining the decision matrix is as follows.

(1) *Determination Evaluation Factors and Comment Set*

The evaluation factors are expressed as $u_1, u_2, \ldots, u_m$, then the evaluation factor set is $U = \{u_1, u_2, \ldots, u_m\}$.

set evaluation indexes of each evaluation factor be u_{ij}, $(i = 1, 2, \ldots, m; j = 1, 2 \ldots, n)$. We can get index set $u_i = \{u_{i1}, u_{i2}, \ldots, u_{ij}, \ldots, u_{im}\}$, $i = 1, 2, \ldots, m; j = 1, 2, \ldots, n$.

Define the comment set as $V = \{v_1, v_2, \ldots, v_p\}$.

(2) *Construct Evaluation Matrix*

Assuming the comment level of index u_{ij}, $(i = 1, 2, \ldots, m; j = 1, 2, \ldots, n)$ is $v_k(k = 1, 2, \ldots, p)$, then the relationship matrix of factor set U mapping to comment set V is R_i:

$$R_i = \begin{bmatrix} r_{i11}, r_{i12}, \ldots, r_{i1p} \\ r_{i21}, r_{i22}, \ldots, r_{i2p} \\ \vdots \quad \vdots \quad \vdots \\ r_{in1}, r_{in2}, \ldots, r_{inp} \end{bmatrix}, \tag{3.3}$$

where r_{ijk} means the comment of factor u_{ij} mapping to comment set, and r_{ijk} can be expressed as

$$r_{ijk} = \left[t_{\tilde{R}ijk}, 1 - f_{\tilde{R}ijk}\right]. \tag{3.4}$$

For qualitative index, the value can be got from experts' evaluation. For quantitative index, its quantitative value is the index value. Normalizing index value, we can get $t_{\tilde{R}ijk}$ and $1 - f_{\tilde{R}ijk}$.

The main calculations are as follows.

Multiply calculation:

$$k \cdot \tilde{A} = \left[k \cdot t_{\tilde{A}}, k \cdot (1 - f_{\tilde{A}})\right]k, \quad k \in [0, 1]. \tag{3.5}$$

Finite sum calculation:

$$\widetilde{A} \oplus \widetilde{B} = \left[t_{\widetilde{A}} \oplus t_{\widetilde{B}}, (1 - f_{\widetilde{A}}) \oplus (1 - f_{\widetilde{B}})\right] = \left[\min\{1, t_{\widetilde{A}} + t_{\widetilde{B}}\}, \min\{1, (1 - f_{\widetilde{A}}) + (1 - f_{\widetilde{B}})\}\right], \quad (3.6)$$

$$b_{ik} = \left[\min\left\{1, \sum_{j=1}^{n} a_{ij} t_{\widetilde{R_{ijk}}}\right\}, \min\left\{1, \sum_{j=1}^{n} a_{ij}\left(1 - f_{\widetilde{R_{ijk}}}\right)\right\}\right], \quad (3.7)$$

where $\widetilde{B}_i$ is a vague subset and b_{ik} $(k = 1, 2, \ldots, p)$ is the evaluation value of k to $\widetilde{B}_i$.

3.2. *D-S Evidence Theory*

The evidence theory, first proposed by Harvard University mathematician A. P. Dempster in the 1960s, aims to use upper and lower probability to solve the multivalued mapping issues. G. Shafer, Dempster's student, has further developed the evidence theory by introducing the concept of belief function to form a mathematical system to deal with uncertainty reasoning based on "evidence" and "portfolio."

Definition 3.1. Suppose Θ is the frame of discernment. If set function $m : 2^{\Theta} \to [0,1]$ (2^{Θ} is the power set of Θ) is to meet $m(\Phi) = 0$, $\sum_{A \subset \Theta} m(A) = 1$, the function m is called the basic probability assignment on Θ; for all $A \subset \Theta$, $m(A)$ is called the basic belief degree.

Definition 3.2. Suppose Θ is the frame of discernment, function $m : 2^{\Theta} \to [0,1]$ is the basic probability assignment on Θ, then the belief function is defined as $\mathrm{Bel} : 2^{\Theta} \to [0,1]$, where $\mathrm{Bel}(A) = \sum_{B \subset A} m(B)$, for all $A \subset \Theta$.

Definition 3.3. If $m(A) > 0$, then A is called the focal element of the belief function Bel. And all focal elements are called its core.

Definition 3.4. If function $Q : 2^{\Theta} \to [0,1]$ is defined by $Q(A) = \sum_{A \subset B} m(B)$, for all $A \subset \Theta$, then Q is called the total belief function of Bel. For all $A \subset \Theta$, $Q(A)$ is called the total belief number of A.

Definition 3.5. Suppose $\mathrm{Bel} : 2^{\Theta} \to [0,1]$ is a belief function on Θ. Functions $\mathrm{Dou} : 2^{\Theta} \to [0,1]$ and $\mathrm{pl} : 2^{\Theta} \to [0,1]$ are defined as for all $A \subset \Theta$ $\mathrm{Dou}(A) = \mathrm{Bel}(\overline{A})$ and $\mathrm{pl}(A) = 1 - \mathrm{Bel}(\overline{A})$, then Dou is called suspicion function of Bel, and pl is called plausibility function. For all $A \subset \Theta$, $\mathrm{Dou}(A)$ is called the suspicion degree of A, and $\mathrm{pl}(A)$ is called the plausibility degree.

Theorem 3.6. *Suppose m_1 and m_2 are two basic probability assignment functions formed based on information obtained from two different information sources,* Bel_1 *and* Bel_2, *in the same frame of discernment Θ. $A_1, A_2, \ldots, A_k$ and $B_1, B_2, \ldots, B_l$ are focal elements of* Bel_1 *and* Bel_2. *If $\sum_{A_i \cap B_j = \phi} m_1(A_i) m_2(B_j) < 1$, the combination of m_1 and m_2 is as follows:*

$$m(A) = \begin{cases} 0, & A = \phi, \\ \dfrac{\sum_{A_i \cap B_j = A} m_1(A_i) m_2(B_j)}{1 - \sum_{A_i \cap B_j = \phi} m_1(A_i) m_2(B_j)}, & A \neq \phi. \end{cases} \quad (3.8)$$

Theorem 3.7. *Suppose $m_1, m_2, \ldots, m_n$ are the corresponding basic probability assignment functions formed based on information obtained from different information sources $\mathrm{Bel}_1, \mathrm{Bel}_2, \ldots, \mathrm{Bel}_n$ in the same frame of discernment Θ. If $\mathrm{Bel}_1 \oplus \mathrm{Bel}_2 \oplus \cdots \oplus \mathrm{Bel}_n$ exists and m is its basic probability assignment function, then*

$$\begin{gathered}
\forall A \subseteq \Theta, \quad A \neq \phi, \\
m(A) = K_n \sum_{A_1 \cap A_2 \cap \cdots \cap A_N} m_1(A_1) m_2(A_2) \cdots m_n(A_n), \\
K_n = \frac{1}{N_n}, \\
N_n = \sum_{A_1 \cap A_2 \cap \cdots \cap A_N \neq \phi} m_1(A_1) m_2(A_2) \cdots m_n(A_n).
\end{gathered} \tag{3.9}$$

3.3. *Design of Comprehensive Evaluation Model*

Suppose there is a multiattribute (index) evaluation problem with comprehensive comment set $V = \{V_1, V_2, \ldots, V_m\}$ and evaluation index set $I = \{I_1, I_1, \ldots, I_n\}$. According to vague set, the decision matrix $R = (R_{ij})_{m \times n}$, $R_{ij} = [t_{ij}, 1 - f_{ij}]$ is got. By synthesis law of vague set, we can convert the vague set R into a real set $G = (g_{ij})_{m \times n}$, $g_{ij} = (t_{ij} + (1 - f_{ij}))/2$.

Different mass functions mean different evaluation results. So it is vital to determine the uncertainty degree of evidences. Theoretically, one index which matches average information better than other indexes is more beneficial for decision making, and the information uncertainty degree of the index is lower, vice versa.

Suppose the matrix G is

$$G = (g_{ij})_{m \times n}, \qquad \overline{g_i} = \frac{1}{n} \sum_{j=1}^{n} g_{ij}, \; i = 1, 2, \ldots, m. \tag{3.10}$$

Define the q-order uncertainty degree of index I_j as

$$\begin{gathered}
\mathrm{DOI}(I_j) = \frac{1}{m} \left[\sum_{i=1}^{m} (r_{ij})^q \right]^{1/q}, \\
r_{ij} = \frac{\min_i \left| g_{ij} - \overline{g} \right| + \xi \min_i \left| g_{ij} - \overline{g} \right|}{\left| g_{ij} - \overline{g} \right| + \xi \min_i \left| g_{ij} - \overline{g} \right|}, \quad i = 1, 2, \ldots, m; \; j = 1, 2, \ldots, n,
\end{gathered} \tag{3.11}$$

where r_{ij} is called gray mean correlation degree with $\xi = 0.5$ in general.

In case of negative number, the normalization method is shown as

$$\overline{g_{ij}} = \frac{g_{ij} - \min_i (g_{ij})}{\min_i (g_{ij}) - \min_i (g_{ij})}. \tag{3.12}$$

Suppose $x = (x_1, x_2, \ldots, x_t)$ is a finite difference information sequence with a length of $t(t \neq 0)$. An index set exists in the form of sequence $x_j \neq 0, j \in J$, $J = \{1, 2, \ldots, t\}$. The mapping function f is defined as information structure operator of finite sequence x:

$$f : x \longrightarrow y y_j = \frac{x_j}{\sum_{k=1}^{t} x_k}. \tag{3.13}$$

Here $y = (y_1, y_2, \ldots, y_t)$ is called mapping sequence of information structure.

The normalized score function matrix can be transformed into mapping sequence of information structure $Y = (y_{ij})_{m\times n}$.

Then the mass function $m_j(i)$ can be constructed:

$$m_j(i) = \left(1 - \mathrm{DOI}(I_j)\right) y_{ij}, \tag{3.14}$$

where $m_j(i)$ is a mass function of V_m to index I_j, $\sum_{i=1}^{m} m_j(i) < 1$. So the mass function of overall uncertainty with respect to the index I_j is shown as

$$m_j(i+1) = 1 - \sum_{i=1}^{m} m_j(i). \tag{3.15}$$

According to the proposed combination rule, the final evaluation results can be calculated after the combination of mass functions of comment set with respect to all indexes.

In summary, steps for comprehensive evaluation based on vague set and D-S evidence theory are as follows.

Step 1. Construct the decision-making matrix R based on the vague set theory.

Step 2. Convert R into real matrix $G = (g_{ij})_{m\times n}$ according to vague combination rule.

Step 3. Calculate the uncertainty degree $\mathrm{DOI}(I_j)$ $j = 1, 2, \ldots, n$ combined with real matrix G and (3.6).

Step 4. Establish the mapping sequence of information structure $Y = (y_{ij})_{m\times n}$.

Step 5. Build up mass function $m_j(i)$ and mass function of overall uncertainty $m_j(i+1)$ on the basis of $Y = (y_{ij})_{m\times n}$ and $\mathrm{DOI}(I_j)$.

Step 6. Fuse evidence information using the D-S combination rule.

Step 7. Make evaluation and decision in principle of the maximizing belief function.

4. Simulation Analysis

Guangdong power system in China, which includes thermal power, wind power, and solar photovoltaic power, is selected to simulation analysis. It is known from Section 2 that the comprehensive benefit evaluation index system of hybrid power system includes the four aspects of economic benefit, environmental benefit, social benefit, and security, which is composed of 13 indexes shown in Table 1. According to data statistics and calculation, the original index value can be got as follows.

The comprehensive comment set is set to be $V = \{v_1, v_2, v_3, v_4, v_5\} = \{\text{best}, \text{better}, \text{good}, \text{worse}, \text{worst}\}$. For quantitative indexes such as voltage qualification rate, power grid frequency rate, average load rate, and power supply reliability rate, their values can be directly calculated by basic statistical data. For qualitative indicators such as debt paying ability, operation ability, saving natural resources, reducing environmental pollution, their values can be decided by comprehensive experts' opinions with specific situations.

According to vague set, we can get the vague matrix R for hybrid power system. Calculate the uncertainty degree $\mathrm{DOI}(I_j)$ and mapping sequence of information structure $Y = (y_{ij})_{m\times n}$. Then we can get mass function $m_j(i)$ and mass function of overall uncertainty $m_j(i+1)$:

$$
R = \begin{array}{cc}
 & \begin{array}{ccccc} v_1 & v_2 & v_3 & v_4 & v_5 \end{array} \\
\begin{array}{c} I_1 \\ I_2 \\ I_3 \\ I_4 \\ I_5 \\ I_6 \\ I_7 \\ I_8 \\ I_9 \\ I_{10} \\ I_{11} \\ I_{12} \\ I_{13} \end{array} &
\left[\begin{array}{ccccc}
[0.72, 0.86] & [0.83, 0.89] & [0.52, 0.63] & [0.24, 0.28] & [0.10, 0.16] \\
[0.68, 0.88] & [0.76, 0.80] & [0.86, 0.93] & [0.27, 0.38] & [0.34, 0.49] \\
[0.92, 0.87] & [0.80, 0.86] & [0.43, 0.49] & [0.34, 0.40] & [0.13, 0.28] \\
[0.67, 0.73] & [0.79, 0.87] & [0.64, 0.73] & [0.41, 0.56] & [0.34, 0.39] \\
[0.64, 0.73] & [0.79, 0.87] & [0.64, 0.73] & [0.41, 0.55] & [0.34, 0.39] \\
[0.71, 0.84] & [0.94, 0.98] & [0.74, 0.82] & [0.51, 0.64] & [0.14, 0.25] \\
[0.75, 0.84] & [0.77, 0.86] & [0.89, 0.90] & [0.23, 0.29] & [0.21, 0.31] \\
[0.77, 0.84] & [0.74, 0.83] & [0.91, 0.96] & [0.23, 0.32] & [0.14, 0.31] \\
[0.68, 0.76] & [0.70, 0.81] & [0.84, 0.92] & [0.18, 0.22] & [0.08, 0.16] \\
[0.82, 0.96] & [0.94, 0.97] & [0.75, 0.96] & [0.34, 0.48] & [0.18, 0.33] \\
[0.79, 0.80] & [0.94, 0.96] & [0.56, 0.63] & [0.29, 0.33] & [0.13, 0.20] \\
[0.84, 0.90] & [0.95, 0.97] & [0.34, 0.41] & [0.23, 0.26] & [0.19, 0.36] \\
[0.75, 0.69] & [0.87, 0.84] & [0.24, 0.33] & [0.17, 0.31] & [0.12, 0.24]
\end{array}\right]
\end{array},
$$

$$
M = \begin{bmatrix}
0.14, 0.12, 0.00, 0.24, 0.11, 0.13, 0.17, 0.20, 0.17, 0.00, 0.24, 0.21, 0.17 \\
0.32, 0.21, 0.37, 0.14, 0.37, 0.29, 0.29, 0.15, 0.15, 0.13, 0.00, 0.18, 0.24 \\
0.14, 0.09, 0.27, 0.28, 0.17, 0.14, 0.00, 0.00, 0.16, 0.21, 0.23, 0.14, 0.00 \\
0.00, 0.00, 0.07, 0.17, 0.19, 0.25, 0.16, 0.23, 0.00, 0.18, 0.15, 0.31, 0.18 \\
0.24, 0.25, 0.13, 0.17, 0.16, 0.19, 0.22, 0.22, 0.39, 0.35, 0.08, 0.16, 0.31
\end{bmatrix}. \tag{4.1}
$$

Set $\theta = v_1, v_2, v_3, v_4, v_5$, $2^\theta = \{\{v_1\}, \{v_2\}, \{v_3\}, \{v_4\}, \{v_5\}, \{v_1, v_2, v_3, v_4, v_5\}\}$. According to D-S combination rule, we can get belief functions of $\{v_1\}$, $\{v_2\}$, $\{v_3\}$, $\{v_4\}$, $\{v_5\}$, $\{v_1, v_2, v_3, v_4, v_5\}$ which are 0.19, 0.45, 0.13, 0.14, 0.08, 0.01, meaning $v_2 \succ v_1 \succ v_4 \succ v_3 \succ v_1$. The belief functions of v_2 is best. According to maximizing principle of belief function, the result of comprehensive benefit evaluation is "better."

In order to validate the proposed evaluation algorithm, three other commonly used algorithms including Fuzzy set theory, Vague set theory, and D-S evidence theory are calculated for comparison. According to Fuzzy set theory and the original index value, the comprehensive evaluation result of hybrid power system is $[v_1, v_2, v_3, v_4, v_5] = [0.2204, 0.2060, 0.1963, 0.1925, 0.1849]$, which means the quality of hybrid power system is "best." According to Vague set theory and the calculated vague index value, the comprehensive evaluation result is $[v_1, v_2, v_3, v_4, v_5]$

Table 1: Comprehensive benefit evaluation index system of hybrid power system.

Evaluation objective	Influence factors	Evaluation indexes	Original index value
Comprehensive benefit	Social benefit	Pulling gross domestic product (I_1)	61.24%
		Improving people's living standard (I_2)	2.99%
		Promoting social employment (I_3)	3.79%
	Environmental benefit	Saving natural resources (I_4)	17.77%
		Reducing environmental pollution (I_5)	6.70%
	Economic benefit	Solvency capacity (I_6)	4.47%
		Operational capacity (I_7)	4%
		Profitability (I_8)	4.50%
		Development capacity (I_9)	5%
	Security	Integrated voltage qualification rate (I_{10})	99.27%
		Grid frequency qualification rate (I_{11})	99.99%
		Average loading rate of provincial grid (I_{12})	80.94%
		Power supply reliability rate (I_{13})	99.81%

$= [[0.7517,0.8414][0.8587,0.9067][0.6760,0.7513][0.3368,0.4229][0.1843,0.3045]]$, the corresponding evaluation value is 0.7966, 0.8827, 0.7137, 0.3799, 0.2444, which means the final evaluation result is "better" and the corresponding evaluation value being 0.8827. According to D-S evidence theory, the belief functions of $\{v_1\}, \{v_2\}, \{v_3\}, \{v_4\}, \{v_5\}, \{v_1, v_2, v_3, v_4, v_5\}$ are 0.19, 0.32, 0.12, 0.16, 0.07, 0.14, which means the result of comprehensive benefit evaluation is "better."

Combine the actual conditions and experts' opinions we know such that the actual comprehensive benefit of hybrid power system in Guangdong province is better, which means that the evaluation results of proposed evaluation model, vague set theory, and D-S evidence theory are all correct but fuzzy set. Therefore we know that fuzzy set has a great limitation in comprehensive evaluation compared to the proposed model. At the same time, the best result of proposed model is 0.45 which is much more than better 0.19 no less than the worst 0.01. Analyze final evaluation result sequence of proposed evaluation model, vague set theory, and D-S evidence theory; it is known that the range of result set of the proposed model is much more apparent than other evaluation algorithms. So the results from different evaluation methods validate that the proposed algorithm based on vague set and D-S evidence theory could obtain satisfying conclusion and decrease uncertainty of decision making.

5. Conclusion

The proportion of clean energy is increasing in recent years. Different power generation models have different advantages and disadvantages. It is of great significance for hybrid power system to evaluate the comprehensive benefits. Analyzing characteristics of hybrid power system, an index system of comprehensive benefit evaluation including economic benefit, environmental benefit, social benefit, and security is established in this paper. Due to advantages of processing abundant uncertain and fuzzy information, vague set is used to determine the decision matrix. Convert vague decision matrix to real one by vague combination rule and determine uncertain degrees of different indexes by grey incidence analysis, then the mass functions of different comment set in different indexes are obtained. Information can be fused in accordance with the D-S combination rule and the evaluation result is got. A simulation of hybrid power system including thermal power, wind power, and photovoltaic power in China is simulated. In order to validate the proposed evaluation model, three other commonly used algorithms including Fuzzy set theory, Vague set theory, and D-S evidence theory are calculated for comparison. The results illustrate that a satisfying conclusion can be obtained and an obvious decrease can be observed in the uncertainty of decision making compared to other commonly used evaluation methods. The actual implementation results prove that the proposed evaluation algorithm based on vague set and D-S evidence theory is effective and practical to evaluate comprehensive benefit of hybrid power system.

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References

[1] R. J. Wai and C. Y. Lin, "Active low-frequency ripple control for clean-energy power-conditioning mechanism," *IEEE Transactions on Industrial Electronics*, vol. 57, no. 11, pp. 3780–3792, 2010.

[2] P. D. C. Wijayatunga and D. Prasad, "Clean energy technology and regulatory interventions for Greenhouse Gas emission mitigation: Sri Lankan power sector," *Energy Conversion and Management*, vol. 50, no. 6, pp. 1595–1603, 2009.

[3] A. Esmin and G. Lambert-Torres, "Application of particle swarm optimization to optimal power systems," *International Journal of Innovative Computing, Information and Control*, vol. 8, no. 3A, pp. 1705–1716, 2012.

[4] J. Park, T. Oh, K. Cho et al., "Reliability evaluation of interconnected power systems including wind turbine generators," *International Journal of Innovative Computing, Information and Control*, vol. 8, no. 8, pp. 5797–5808, 2012.

[5] A. Abro and J. Mohamad-Saleh, "Control of power system stability-reviewed solutions based on intelligent systems," *International Journal of Innovative Computing, Information and Control*, vol. 8, no. 10A, pp. 6643–6666, 2012.

[6] P. Tavner, "Wind power as a clean-energy contributor," *Energy Policy*, vol. 36, no. 12, pp. 4397–4400, 2008.

[7] K. Kaygusuz, "Wind power for a clean and sustainable energy future," *Energy Sources, Part B*, vol. 4, no. 1, pp. 122–133, 2009.

[8] A. Nishimura, Y. Hayashi, K. Tanaka et al., "Life cycle assessment and evaluation of energy payback time on high-concentration photovoltaic power generation system," *Applied Energy*, vol. 87, no. 9, pp. 2797–2807, 2010.

[9] K. Morison, L. Wang, and P. Kundur, "Power system security assessment," *IEEE Power and Energy Magazine*, vol. 2, no. 5, pp. 30–39, 2004.

[10] Y. Wei, D. Niu, and G. Wang, "Comprehensive benefit evaluation of thermal-wind-hydraulic power joint operation based on combined weight," *East China Electric Power*, vol. 4, pp. 1–5, 2012.

[11] C. He, F. Kai, and Z. Quan, "et al. Investment evaluation system development based on unified information platform for future smart grid," *Energy Procedia*, vol. 12, pp. 10–17, 2011.

[12] Y. Jing, H. Bai, and J. Wang, "A fuzzy multi-criteria decision-making model for CCHP systems driven by different energy sources," *Energy Policy*, vol. 42, pp. 286–296, 2012.

[13] S. Hu and L. Wang, "A comprehensive analysis of the cogeneration units to the thermal system transformation," *Energy Procedia*, vol. 17, no. B, pp. 1169–1176, 2012.

[14] Q. Sun, X. Ge, L. Liu et al., "Review of smart grid comprehensive assessment systems," *Energy Procedia*, vol. 12, pp. 219–229, 2011.

[15] A. Hepbasli, "A key review on exergetic analysis and assessment of renewable energy resources for a sustainable future," *Renewable and Sustainable Energy Reviews*, vol. 12, no. 3, pp. 593–661, 2008.

[16] R. Laleman, J. Albrecht, and J. Dewulf, "Life cycle analysis to estimate the environmental impact of residential photovoltaic systems in regions with a low solar irradiation," *Renewable and Sustainable Energy Reviews*, vol. 15, no. 1, pp. 267–281, 2011.

[17] G. Shafer, *A Mathematical Theory of Evidence*, Princeton University Press, Princeton, NJ, USA, 1976.

[18] M. Beynon, D. Cosker, and D. Marshall, "An expert system for multi-criteria decision making using Dempster Shafer theory," *Expert Systems with Applications*, vol. 20, no. 4, pp. 357–367, 2001.

[19] S. Le Hégarat-Mascle, D. Richard, and C. Ottlé, "Multi-scale data fusion using Dempster-Shafer evidence theory," *Integrated Computer-Aided Engineering*, vol. 10, no. 1, pp. 9–22, 2003.

[20] V. Kaftandjian, O. Dupuis, D. Babot, and Y. M. Zhu, "Uncertainty modelling using Dempster-Shafer theory for improving detection of weld defects," *Pattern Recognition Letters*, vol. 24, no. 1–3, pp. 547–564, 2003.

[21] S. Fabre, A. Appriou, and X. Briottet, "Presentation and description of two classification methods using data fusion based on sensor management," *Information Fusion*, vol. 2, no. 1, pp. 49–71, 2001.

[22] C. R. Parikh, M. J. Pont, and N. Barrie Jones, "Application of Dempster-Shafer theory in condition monitoring applications: a case study," *Pattern Recognition Letters*, vol. 22, no. 6-7, pp. 777–785, 2001.

[23] P. Wang, N. Propes, N. Khiripet, Y. Li, and G. Vachtsevanos, "Integrated approach to machine fault diagnosis," in *Proceedings of the IEEE Annual Textile, Fiber and Film Industry Technical Conference*, pp. 59–65, Atlanta, Ga, USA, May 1999.

[24] R. W. Jones, A. Lowe, and M. J. Harrison, "A framework for intelligent medical diagnosis using the theory of evidence," *Knowledge-Based Systems*, vol. 15, no. 1-2, pp. 77–84, 2002.

[25] X. Su, P. Shi, L. Wu et al., "A novel approach to filter design for T-S fuzzy discrete-time systems with time-varyingdelay," *IEEE Transactions on Fuzzy Systems*. In press.

[26] Q. Zhou, P. Shi, J. Lu et al., "Adaptive output feedback fuzzy tracking control for a class of nonlinear systems," *IEEE Transactions on Fuzzy Systems*, vol. 19, no. 5, pp. 972–982, 2011.

[27] L. Wu, X. Su, P. Shi, and J. Qiu, "Model approximation for discrete-time state-delay systems in the TS fuzzy framework," *IEEE Transactions on Fuzzy Systems*, vol. 19, no. 2, pp. 366–378, 2011.

[28] L. Wu, X. Su, P. Shi, and J. Qiu, "A new approach to stability analysis and stabilization of discrete-time T-S fuzzy time-varying delay systems," *IEEE Transactions on Systems, Man, and Cybernetics B*, vol. 41, no. 1, pp. 273–286, 2011.

[29] J. Zhang, P. Shi, and Y. Xia, "Robust adaptive sliding-mode control for fuzzy systems with mismatched uncertainties," *IEEE Transactions on Fuzzy Systems*, vol. 18, no. 4, pp. 700–711, 2010.

[30] S. K. Nguang, P. Shi, and S. Ding, "Fault detection for uncertain fuzzy systems: an LMI approach," *IEEE Transactions on Fuzzy Systems*, vol. 15, no. 6, pp. 1251–1262, 2007.

[31] W. L. Gau and D. J. Buehrer, "Vague sets," *IEEE Transactions on Systems, Man and Cybernetics*, vol. 23, no. 2, pp. 610–614, 1993.

[32] X. Geng, X. Chu, and Z. Zhang, "A new integrated design concept evaluation approach based on vague sets," *Expert Systems with Applications*, vol. 37, no. 9, pp. 6629–6638, 2010.

[33] D. Zhang, J. Zhang, K. K. Lai, and Y. Lu, "An novel approach to supplier selection based on vague sets group decision," *Expert Systems with Applications*, vol. 36, no. 5, pp. 9557–9563, 2009.

[34] S. Wan, "Applying interval-value vague set for multi-sensor target recognition," *International Journal of Innovative Computing, Information and Control*, vol. 7, no. 2, pp. 955–963, 2011.