Notice of Retraction

"A Hybrid Fuzzy Multiple Criteria Decision-making Approach for Comprehensive Performance Research and Evaluation of RE-CCHP System,"
by Jinhai Yang; Jiahui Wu; Saniye Maihemuti; Haiyun Wang; Weiqing Wang
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A hybrid fuzzy multiple criteria decision-making approach for comprehensive performance research and evaluation of RE-CCHP system

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ABSTRACT The combined cooling heating and power (CCHP) systems have been drawing high attention due to its energy-saving, environmentally friendly, and cost-saving characteristics. In order to utilize the abundant renewable energies (RE) efficiently, and meet the demand of diversity of energy uses, RE is proposed to realize a CCHP system. However, various forms of energy use can lead to complex control and higher cost. Therefore, new methods are needed to evaluate the advantages and disadvantages of a renewable energies based on CCHP, called RE-CCHP system. In this paper, one of the buildings in Western China is selected as a research object, and the separate power (SP) system and CCHP system are taken as references. Twenty-six different indexes of a RE-CCHP system are constructed based on the environment, society, economy, and technology criteria. Simultaneously, the subjective and objective weights of the indexes are calculated by using the fuzzy decision-making trial and evaluation laboratory and anti-entropy weight (Fuzzy-DEMATEL-AEW), respectively. Then, the comprehensive weights are calculated using the matrix theory. As a result, the important indexes and two operation modes (FEL and FTL) of different systems are compared and analyzed according to the the comprehensive weight value. Meanwhile, the VIKOR method is used to evaluate and analyze the performance of three systems. At the end, sensitivity analysis is carried out to illustrate the rationality and feasibility of the proposed method.

INDEX TERMS Fuzzy-DEMATEL, AEW, VIKOR, RE-CCHP, PV energy, Wind energy

I. INTRODUCTION

At present, high energy production efficiency, environmentally friendly characteristic, and fossil fuels availability are mainstream topics in the power engineering. The worldwide energy policy is focused on energy production improvement and energy sources diversification [1]. Accordingly, the development of clean energy is one of today's most relevant topics. Wind and photovoltaic (PV) energies are the most commercially promising renewable energies (RE), as well as ones of the most dynamic because they are low-cost and can be exploited inexhaustibly. Moreover, both wind and PV power can lessen air and water pollution and slow down global warming. In recent years, the worldwide demand for wind energy has grown steadily. According to the State Grid Corporation of China, Chinese wind and PV powers installed capacity growth increasing drastically in recent decades, as presented in Fig.1.

Due to the gradual depletion of fossil fuels, development of renewable energy, and increasing attention to environmental issues, the combined cooling heating and power (CCHP) systems are regarded as an effective organization form of distributed energy supply security units, with a low consumption highly-efficient utilization of primary energy, low emissions, and high reliability [2-3]. Therefore, the CCHP system was proposed and concerned, due to several advantages as follow [4]:

- simultaneous provision of heating, cooling and power.
- higher total primary energy efficiency.
- less pollution gas emissions.

Nomenclature		*TCR*	total cost rate
CCHP	combined cooling, heating and power	*CDEC*	carbon dioxide emissions cost
SP	separate system	MCDM	multi-criteria decision making
RE	renewable energies	TFN	triangular fuzzy number
FEL	following electrical load	*E*	electricity (kW)
FTL	following thermal load	Q_c	cooling
DEMETEL	decision-making trial and evaluation laboratory	Q_h	heating
AEW	anti-entropy weight	b	boiler
VIKOR	(the acronym is in Serbian: Više-Kriterijumska Optimizacija I Kompromisno Rešenje, meaning the multi-criteria optimization and compromise solution)	AC	absorbtion chiller
PGU	power generation unit	EC	electric chiller
COP	coefficient of performance	P	power
ATCS	annual total cost saving	rec	recovered
PER	primary energy rate	grid	electricity network
PES	primary energy saving	η	efficiency
PEC	primary energy consumption	μ	emission conversion
PESR	primary energy ratio	W	wind power
FESR	fuel energy saving ratio	PV	photovoltaic
OC	operation cost	ω	weight

- flexible adjustment for the ratio of electricity to heating

Hence, CCHP systems have been widely recognized as an alternative method to solve the problems of energy consumption and environmental protection, and they are considered to be potential energy supply systems for various commercial complexes and civil buildings such as hospitals, offices, and hotels [5].

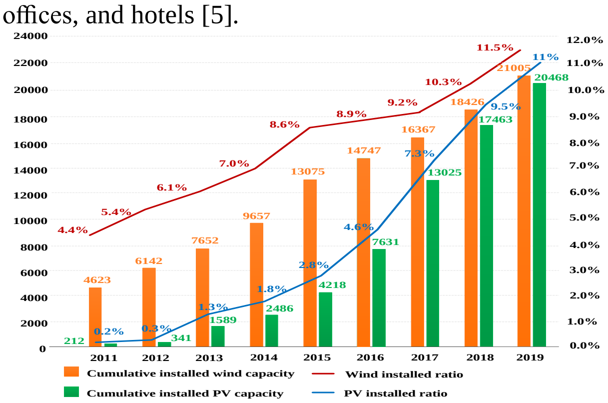

FIGURE 1. **Accumulative installed capacity and proportion of wind and PV power in China from 2011 to 2019**

At present, the proper use of CCHP equipment and design of a CCHP system based on abundant RE, called RE-CCHP system are receiving high attention. A RE-CCHP system not only can improve the technology, evaluation, decision-making levels, integration efficiency, and integration quality of a power grid but also denotes a successful method to decrease environmental pollution and accommodate the instabilities of renewable energy simultaneously. As an energy-efficient technology, a RE-CCHP system is broadly identified as a promising alternative to meet and solve the energy-related problems, such as increasing energy demand, increasing energy cost, energy supply security and reliability, and environmental and social concerns [6]. Therefore, it is of great necessity to construct a corresponding criteria system and evaluation method. With the aim to evaluate the RE-CCHP system performance comprehensively, some studies focused on the optimization of CCHP systems, were simultaneously performed concerning the energetic, economic, environmental protection, and social aspects. The primary energy consumption (*PEC*), primary energy rate (*PER*), primary energy saving (*PES*), fuel energy saving ratio (*FESR*), energy-efficiency, operation cost (*OC*), total cost rate (*TCR*), annual total cost saving (*ATC*), energy cost, exergetic efficiency and gross benefit, as well as carbon dioxide emissions cost (*CDEC*) [7-10] have been often employed to evaluate comprehensively the technical performance of RE-CCHP systems. Kang et al. [11] compared three operational modes to analyze the benefits of a CCHP system based on primary energy consumption, carbon dioxide emissions, annual total cost and system efficiency. The results showed that the largest *ATC*, *OC*, carbon dioxide emissions cost (*CDE*) and *PEC* reductions reached 10.3%, 38.3%, 50.8% and 77.4%, respectively. The above-mentioned researches revealed that the optimized CCHP system had better performance compared with conventional separate power (SP) system in most cases. The environmental protection, *PEC*, and economic characteristics of distributed energy system were taken as the comprehensive evaluation indexes, and a comparative analysis was performed according to different operation strategies of the CCHP system [3]. Yousefi et al. [12] proposed comprehensive criteria based on *ATC*, *PEC* and *CDE* to optimize the operation of CCHP system under different load demands and evaluate system performance. As for the operation mode of a CCHP system: Wang et al. [13] proposed life cycle assessment optimization to find the optimal

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configuration of the CCHP system operating in the following electrical load (FEL) and following thermal load (FTL) mode. The results indicated that FTL is better than FEL when environmental compensation of excess products taken into consideration. Li et al. [14] found that considering feed-in tariff and carbon emission, FTL is the best choice, and FEL is the best choice without the consideration of feed-in tariff and carbon emission. Wang and Yang proposed a hybrid CCHP system driven by biomass and PV energy and investigated and analyzed the thermodynamic performances, including the primary energy ratio, exergy efficiency, and carbon emission reduction ratio under design conditions [15]. The results indicated that the biomass subsystem had a greater contribution than the PV subsystem to the primary energy ratio and exergy efficiency priority, while the PV subsystem was more beneficial to the emission reduction. The relevant research has been mainly aimed at other types of CCHP system evaluation, such as in [16], wherein the selected comprehensive performance indexes, including the annual total operating costs, primary energy consumption, and CO_2 emissions, were used as the objective function of optimization, establishing the gas CCHP system evaluation methods, whose research ideas and methods can be used for reference. The CCHP system and many other factors, such as technology, economy, environment, and society, interact and restrict to each other [17]. The above research mainly analyzed the benefits of CCHP from the aspects of economy, techno-economy and environment, but focused on the benefits from one aspect only, rather than making a comprehensive evaluation.

With the increase in the complexity and multiplicity of energy planning, a single objective optimization/analysis is no longer a prevalent approach. The multi-criteria decision making (MCDM) is considered as an evaluation structure to solve environmental, socio-economic, technical, and institutional barriers involved in energy planning [18]. The MCDM is a well-known operation research field and the most well-known branch of decision making. It is a branch of a general class of operation research models that can be applied to complex decision making when a lot of criteria are involved. The most commonly used methodologies are the Analytic Hierarchic Process (AHP), the Preference Ranking Organization Method for Enrichment and Evaluations (PROMETHEE), the Elimination et Choix Tradusiant la Realité (ELECTRE) [18], a decision-making trial and evaluation laboratory (DEMATEL), and the Analytic Network Process (ANP) [19], an Entropy Weight (EW) [20], a simple additive weighting (SAW), the grey relational analysis (GRA), Technique for Order Performance by Similarity to Ideal Solution (TOPSIS) and multi-objective optimization on the basis of ratio analysis (MOORA) [21], the Više-Kriterijumska Optimizacija I Kompromisno Rešenje, meaning the multi-criteria optimization and compromise solution (VIKOR) [22], and the Data Envelopment Analysis (DEA) [23]. The MCDM methods (e.g., AHP, Electre, PROMETHEE, etc.) have been usually used to rank the alternative distributed energies (DEs) by multiple indexes based on evaluation [18]. Ren et al. [24] combined the AHP and PROMETHEE into a multi-criteria evaluation method for selecting the best distributed residential energy systems in Japan. Fu et al. [20] employed the interval entropy weight method to address the uncertainties existing in distributed generation planning when it was difficult to obtain the exact numerical values with respect to the evaluation criteria. Kaya and Kahraman [22] applied the AHP to determine the weights of the evaluation criteria, and VIKOR was employed to rank the alternative renewable energy options by considering the criteria from technical, economic, environmental, and social aspects. In order to evaluate the RE-CCHP system more comprehensively, this paper establishes a more comprehensive and rich index system based on Reference [25], and obtains a more reasonable and accurate evaluation index weight from both subjective and objective aspects. To evaluate a RE-CCHP system, we explore an integrated fuzzy DEMATEL-AEW-VIKOR approach to the RE-CCHP system. The decision information is investigated and collected using the linguistic variables, and the weighting average technique integrating subjective weight with objective weight is combined with the fuzzy VIKOR procedure. In order to the comparison of adding RE to CCHP system, the RE-CCHP system is compared with other three systems: (1) SP system; (2) CCHP system; (3) RE-CCHP system in two modes.

This paper is organized as follows. Literature review on principle and control strategy analysis of RE-CCHP systems is presented in Section II. In Section III, the related criteria and framework of the proposed method and identification of evaluation indexes in four main types and their hierarchy are presented. In Section IV, a novel hybrid MCDM methodology, namely the fuzzy DEMATEL-AEW-VIKOR approach, is proposed to determine the weights of evaluation indexes. In Section V, the proposed building is introduced, and subjective, objective, and total weights of evaluation indexes are calculated. In Section VI, according to the calculated weights, the important indexes of each system criterion level are analyzed and compared. In Section VII, the VIKOR method is used to rank and compare three alternative systems, and sensitivity analysis on the proposed method with the other MCDM method is provided. Finally, conclusion and our future research directions are given in Section VIII.

II. PRINCIPLE AND CONTROL STRATEGY ANALYSIS OF RE-CCHP SYSTEM

A. PRINCIPLE AND ENERGY FLOWCHART OF RE-CCHP SYSTEM

In this study, a SP system as a reference system, is compared to a RE-CCHP system. The energy flowchart of the SP system and RE-CCHP systems are shown in Fig. 2, wherein on the downside the SP system, and on the upside, the RE-CCHP system is shown. The energy demands of a building include: (i) electric energy use E; (ii) cool demand for space cooling Q_c; and (iii) heat demand for space heating and domestic hot water Q_h.

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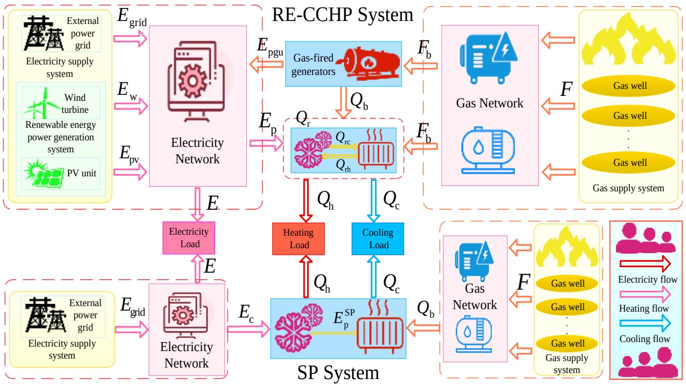

FIGURE 2. **Energy flowchart of a RE-CCHP system**

The capacity, price, efficiency, and durability of the equipment involved in the RE-CCHP system are given in Table I.

TABLE I
UNIT CAPACITY, PRICE, EFFICIENCY AND DURABILITY OF THE EQUIPMENT OF THE RE-CCHP SYSTEM

Parameter Equipment	Per Capacity (kW)	Unit Price()	Efficiency	durability
Gas boiler	200	10	0.91	20
Gas engine	110	80	——	25
PV power	10	13	——	25
Wind power	10	18	——	25
AC	500	190	1.33	20
EC	130	160	3.1	20

B. CONVENTIONAL SP SYSTEM

A conventional SP system is compared with a CCHP system. The cooling in the SP system adopts the electric chiller, and the heat comes from gas boiler and is distributed to users through heating coils. The electricity needed by building and chiller is from the local electricity grid. The total electrical energy from the grid E_{grid}^{SP} is given by:

$$E_{grid}^{SP} = E + E_c + E_p^{SP}, \quad E_p^{SP} = 0.26\left(E_c + \frac{Q_h}{3Q_c}\right) \tag{1}$$

where E_c denotes the electricity supplied to the chiller, and E_p^{SP} is the additional electrical energy used by distribution equipment such as pumps and fans [26].

The electricity needed by the chiller can be expressed as:

$$E_c = \frac{Q_c}{COP_e} \tag{2}$$

where COP_e denotes the coefficient of performance (*COP*) of an electric chiller.

Considering the energy loss of the grid during the transmission, the total electric energy from the grid is converted to the fuel energy consumption as follows:

$$F_e^{SP} = \frac{E_{grid}^{SP}}{\eta_e^{SP}\eta_{grid}} \tag{3}$$

where η_e^{SP} and η_{grid} are the power generation efficiency and grid distribution efficiency, respectively.

The fuel energy consumption of a heating system is computed by:

$$F_b^{SP} = \frac{Q_b}{\eta_b^{SP}} = \frac{Q_h}{\eta_b^{SP}\eta_h^{SP}} \tag{4}$$

where Q_b denotes the output heat of a boiler, and η_b^{SP} and η_h^{SP} denote the efficiencies of the boiler and heating coil, respectively.

Therefore, the total fuel energy consumption is calculated by combining refer to (1) - (4) as follows:

$$F^{SP} = \frac{E}{\eta_e^{SP}\eta_{grid}} + \frac{E_p^{SP}}{\eta_e^{SP}\eta_{grid}} + \frac{Q_c}{COP_e\eta_e^{SP}\eta_{grid}} + \frac{Q_h}{\eta_b^{SP}\eta_h^{SP}} \tag{5}$$

C. RE-CCHP SYSTEM

The energy flowchart of a RE-CCHP system is shown on the upside of Fig. 2. The electricity supply system called power generation unit (PGU) includes external power grid, wind power and PV power. PV power not only can satisfy electric demand, but also can satisfy heating demand by solar collector. The electricity generated by gas turbines and electricity supply system are used to meet electricity demand. When the power generation of gas turbine and electricity supply system is lower than the electrical load, the power shortage is purchased from grid. When the power generation is higher than the electrical load, the excess power can be sold to grid. The flue gas generated by gas turbine is recycled by waste heat recovery boiler to provide thermal load. The PV power is used to convert into heat energy to help provide thermal load. The thermal load consists of steam load used directly for production, heating load produced by heating exchanger and cooling load produced by absorption chiller. The insufficient thermal load is provided by auxiliary boiler.

The balance of the electric energy in a CCHP system is expressed as:

$$E_{grid} + E_{pgu} + E_w + E_{pv} = E + E_p + E_{ec} \tag{6}$$

where E_{grid} denotes the electricity from the grid to the RE-CCHP system, E_{pgu} denotes the electricity generated by a PGU, E_w denotes the electricity generated by wind power, E_{pv} denotes the electricity generated by PV power, E denotes the electric energy uses of building, E_p denotes the parasitic electric energy consumption of the RE-CCHP system, and lastly, E_{ec} denotes the electric energy consumption of electric chiller providing the building cooling.

The electricity used by an electric chiller is calculated by:

$$E_{ec} = \frac{Q_{ec}}{COP_e} \tag{7}$$

where Q_{ec} denotes the cooling produced by the electric chiller, and COP_e denotes the *COP* of the electric chiller.

The PGU fuel energy consumption, E_{pgu}, can be estimated as:

$$F_{pgu} = \frac{E_{pgu}}{\eta_e} \tag{8}$$

where η_e denotes the PGU generation efficiency.

The recovered waste heat from the prime mover Q_r can be expressed as:

$$Q_r = F_{pgu}\eta_{rec}(1-\eta_e) \tag{9}$$

where η_{rec} denotes the heat recovery system efficiency.

The heat supplied to the cooling system and heating coil is given by:

$$Q_r + Q_b = Q_{rc} + Q_{rh} \tag{10}$$

where Q_b denotes the supplementary heat from the boiler, and Q_{rc} and Q_{rh} denote the heat amounts supplied to the absorption chiller and heating coil, respectively.

The heat amounts required by the absorption chiller and heating coil to handle a part of the cooling load and all the heating load is respectively estimated as:

$$Q_{rc} = \frac{Q_{ac}}{COP_{ac}} \tag{11}$$

and

$$Q_{rh} = \frac{Q_h}{\eta_h} \tag{12}$$

where COP_{ac} denotes the COP of the absorption chiller, Q_{ac} denotes the cool produced by the absorption chiller, Q_h denotes the heat demand for space heating and domestic hot water, and η_h denotes the efficiency of a heating coil (in this paper, for simplicity, it is assumed that the transmission efficiency of domestic hot water is equal to η_h).

The supplementary fuel energy consumption to a boiler, F_b, can be expressed as:

$$F_b = \frac{Q_b}{\eta_b} = \frac{Q_{rc} + Q_{rh} - Q_r}{\eta_b} \tag{13}$$

where η_b denotes the back-up boiler efficiency.

The balance of the cooling load of a building is given by:

$$Q_c = Q_{ec} + Q_{ac} \tag{14}$$

where Q_c denotes the cool demand for space cooling.

Here, x is defined as a ratio of cool provided by the electric chiller to the cooling load, and it is expressed as:

$$x = \frac{Q_{ec}}{Q_c} \tag{15}$$

and here, it is called the ratio of electric cooling to the cooling load. When x = 0, the cooling system adopts the absorption chiller, and when x = 1, the electric chiller is employed to provide building cooling; otherwise, the cooling system adopts mixed chillers.

Therefore, the on-site fuel energy consumption $F_{on\text{-}site}$ is calculated by:

$$F_{on\text{-}site} = F_{pgu} + F_b \tag{16}$$

and the total fuel energy consumption is given by:

$$F = F_{on\text{-}site} + \frac{E_{grid}}{\eta_e^{SP}\eta_{grid}} \cdot U \tag{17}$$

where η_e^{SP} denotes the generation efficiency of the SP, and η_{grid} denotes the transmission and distribution efficiency of the electricity grid, and

$$U = \begin{cases} 1, & E_{grid} \geq 0 \\ 0, & E_{grid} < 0 \end{cases} \tag{18}$$

D. OPERATING STRATEGY OF RE-CCHP SYSTEM

It is of great significance to select the most appropriate operation mode and dispatching strategy for improving the performance of the energy supply system. After years of operation experience, a RE-CCHP system usually takes into account the economy, energy efficiency, and environmental protection of the system. The RE-CCHP system adopts the following two operation modes: FEL and FTL [27].

(1) FEL operation mode

The FEL operation strategy refers to the coordinated dispatch of wind and PV power units, gas turbines, and urban power grids, giving priority to the real-time balance of electric power and determining the generation capacity according to the electric load required by a building. When the electricity generated by the wind-PV-driven generators and gas turbines does not meet the demand for the electric load, it is supplemented by the external power grid. On the other hand, when the heat generated by the internal combustion engine and the PV collector does not meet the demand for cooling and heating load, it is supplemented by an electric refrigerator. When the recovered heat is not enough, the boiler begins to run to supplement the additional heat. RE-CCHP system would not export excess electricity to grid in this operation mode while the surplus heat may be exhausted.

The operating condition and the total primary energy consumption are expressed in (19)-(23) as follows:

Test condition: $E + E_p \geq F_{max}\eta_e$ (19)

If Test condition = True then:

$$F = F_{max} + \frac{Q_b}{\eta_b} \cdot U + \frac{E + E_p - F_{max}\eta_e}{\eta_e^{SP}\eta_{grid}} \tag{20}$$

where

$$Q_b = \frac{(1-x)Q_c}{COP_{ch}} + \frac{Q_h}{\eta_h} - F_{max}(1-\eta_e)\eta_{rec} \tag{21}$$

If Test condition = False then:

$$F = \frac{E + E_p}{\eta_e} + \frac{Q_h}{\eta_h} \cdot U \tag{22}$$

where

$$Q_b = \frac{(1-x)Q_c}{COP_{ch}} + \frac{Q_h}{\eta_h} - \frac{E + E_p}{\eta_e}(1-\eta_e)\eta_{rec} \tag{23}$$

(2) FTL operation mode

The FTL operation strategy refers to the coordinated dispatch of the internal combustion engine and PV collector to give priority to the balance of heat load energy flow, and determine its power generation according to the heat load required by the building. The heat load of the system includes two demands: refrigeration demand and heating demand. When the heat generated by the system does not meet the demand for cold and heat load, it is supplemented by the electric refrigerators and electric boilers. On the other hand, when the electricity generated by the system does not meet the demand of electric load, it is supplemented by the external power grid, and the remaining electricity is sold on the eternal grid.

Assuming the maximum input fuel energy F_{max} of the PGU, the operating conditions and the achievable results are expressed in terms of the total fuel energy consumption by refer to (24) - (28) as follows:

Test condition: $\frac{(1-x)Q_c}{COP_{ch}} + \frac{Q_h}{\eta_h} \geq F_{max}(1-\eta_e)\eta_{rec}$ (24)

If Test condition = True then:

$$F = F_{\text{max}} + \frac{\frac{(1-x)Q_{\text{c}}}{COP_{\text{ch}}} + \frac{Q_{\text{h}}}{\eta_{\text{h}}} - F_{\text{max}}(1-\eta_{\text{e}})\eta_{\text{rec}}}{\eta_{\text{b}}} + \frac{E_{\text{grid}}}{\eta_{\text{e}}^{\text{SP}}\eta_{\text{grid}}} \cdot U \quad (25)$$

where

$$E_{\text{grid}} = E + E_{\text{p}} + \frac{xQ_{\text{c}}}{COP_{\text{e}}} - F_{\text{max}}\eta_{\text{e}} \quad (26)$$

If Test condition = False then:

$$F = \frac{\frac{(1-x)Q_{\text{c}}}{COP_{\text{ch}}} + \frac{Q_{\text{h}}}{\eta_{\text{h}}}}{(1-\eta_{\text{e}})\eta_{\text{rec}}} + \frac{E_{\text{grid}}}{\eta_{\text{e}}^{\text{SP}}\eta_{\text{grid}}} \cdot U \quad (27)$$

where

$$E_{\text{grid}} = E + E_{\text{p}} + \frac{xQ_{\text{c}}}{COP_{\text{e}}} - \frac{\frac{(1-x)Q_{\text{c}}}{COP_{\text{ch}}} + \frac{Q_{\text{h}}}{\eta_{\text{h}}}}{(1-\eta_{\text{e}})\eta_{\text{rec}}}\eta_{\text{e}} \quad (28)$$

III. IDENTIFICATION OF EVALUATION INDEXES AND THEIR HIERARCHY

A RE-CCHP system has many forms of energy output, and there are many different attributes of the modules. Therefore, it is impossible to get a comprehensive evaluation result by analyzing a RE-CCHP system from only one aspect. Namely, the evaluation criteria of a system should be put forward from many aspects. The evaluation system is the basis of the comprehensive evaluation, and the selection of the index is an important step to the comprehensive evaluation. The primary goal of a general energy production system is to supply sufficient energy to meet user needs. However, with the increasing depletion of energy and deterioration of environmental problems, not only the balance of energy supply, energy demand, and high energy efficiency should be pursued, but also the factors of the system economy, energy efficiency, and environmental protection should be considered. According to the actual conditions and the above relevant literature, the selected indicators include four attributes of environment, society, economy, and energy efficiency technology. Each attribute selects typical quantitative indexes such as CO_2 emissions, social benefits, operation and maintenance costs or qualitative indexes such as noise, land occupation, and social benefits.

A. ENVIRONMENTAL ATTRIBUTE P_1

The system structure has an important impact on the power system operation mode, clean energy consumption, transmission loss rate, and so on, which indirectly determines the environmental protection of the power system. Due to the increasing emphasis on environmental issues, specifically, China positive commitment and action to cope with climate change, the power grid planning has to take into account the requirements for environmental protection. In general, the environmental protection indexes are indispensable to evaluate the quality of power grid planning. The environmental protection indexes used in this paper include the CO_2 emission, NO_x emission, noise, covering area, the mitigation of the reliance on fossil fuels, and penetrations of renewable energy source.

The amount of CO_2 emission from a RE-CCHP system can be estimated by the emission conversion factor as follows:

$$CO_2E = \mu_{CO_2,\text{f}}F_{\text{on-site}} + \mu_{CO_2,\text{e}}E_{\text{grid}} \quad (24)$$

where $\mu_{CO_2,\text{f}}$ and $\mu_{CO_2,\text{e}}$ denote the emission conversion factors of natural gas and electricity from the grid, respectively. Referring to the definition of the PES, the amount of the CO_2 emission reduction (CO_2ER) of a RE-CCHP system over an SP system can be calculated by:

$$CO_2E = \frac{CO_2E^{\text{SP}} - CO_2E}{CO_2E^{\text{SP}}} = 1 - \frac{CO_2E}{CO_2E^{\text{SP}}} \quad (25)$$

The value of CO_2ER shows the environmental benefits achieved by using RE-CCHP systems instead of SP systems.

B. SOCIAL ATTRIBUTE P_2

With the increasing demands of the grid-connected power grid and users, which begin to pay attention to the social benefits of electricity such as electricity price and power quality the social indexes have become one of the basic requirements of power grid planning, which includes the social benefits, individual operating post, client energy quality and cost of electricity purchased by customers. Customer comfort and satisfaction are also one of the important social indexes, but they are not considered in this work.

C. ECONOMICAL ATTRIBUTE P_3

The economy is not only the most intuitive index reflecting transmission network planning scheme but also the index concerned by decision makers. With the expansion of power grid and a large-scale interconnection of renewable energy, system economy has become a hot concern in the power grid, and it includes the capitalized cost, annual operation cost, maintenance cost, equipment cost, renewable energy system cost, fuel cost, and equipment durability.

Similarly, to measure the economic benefits of a RE-CCHP system over an SP system, the annual total cost saving (*ATCS*) is defined as a ratio of the annual saving cost of a RE-CCHP system in comparison to SP system to the annual cost of an SP system, which is expressed as:

$$ATCS = \frac{ATC^{\text{SP}} - ATC}{ATC^{\text{SP}}} = 1 - \frac{ATC}{ATC^{\text{SP}}} \quad (26)$$

D. TECHNICAL ATTRIBUTE P_4

Technology is the most important part of power grid planning and operation. Namely, technology is the basis, so long as the technical problems of the system are guaranteed to a certain extent, the environmental protection, sociality, and economy can be guaranteed. Technical attribute includes the primary energy consumption, primary energy ratio, power quality of primary energy, renewable energy generation ratio, power system security and reliability, the capability of handling a large amount of data transfer, and black out restoration ability.

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The *PER* is defined as a ratio of primary energy utilization. It represents a satisfactory criterion to evaluate a RE-CCHP system and it is expressed as:

$$PER = \frac{E + Q_c + Q_h}{F} \tag{27}$$

To measure the benefit of a RE-CCHP system over an SP system, the *PES* is defined as the ratio of the saved energy of the RE-CCHP system over the SP system to the energy consumption of the SP system, which is given by:

$$PES = \frac{F^{SP} - F}{F^{SP}} = 1 - \frac{F}{F^{SP}} \tag{28}$$

The evaluation indexes of a RE-CCHP system are given in Fig. 3.

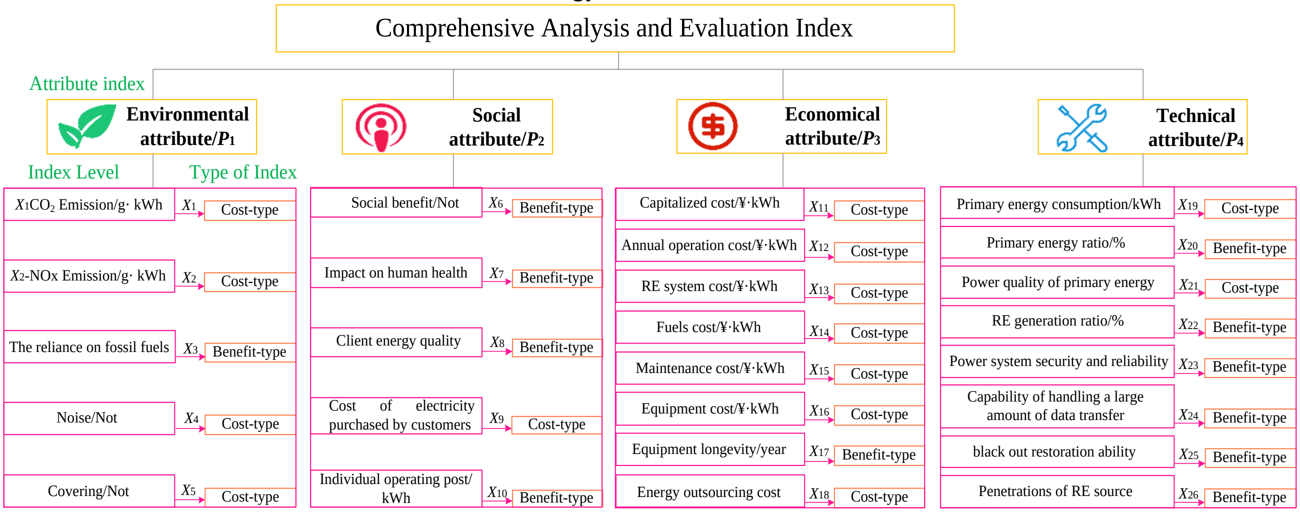

FIGURE 3. The evaluation indexes of a RE-CCHP system

IV. MCDM METHODS FOR COMPREHENSIVE EVALUATION STUDY

The MCDM method can provide a comprehensive and reasonable evaluation of a RE-CCHP system based on multiple parameters, including a variety of attributes and their overall characteristics which are influenced by many factors. As discussed previously, the essential step of the MCDM method analysis is an appropriate calculation of weights for the selected indexes. Therefore, this study combines the Fuzzy-DEMATEL for the calculation of subjective weights and the AEW method for the calculation of objective weights. Finally, based on VIKOR method, a comprehensive evaluation of weighting is performed. The calculation process is shown in Fig. 4.

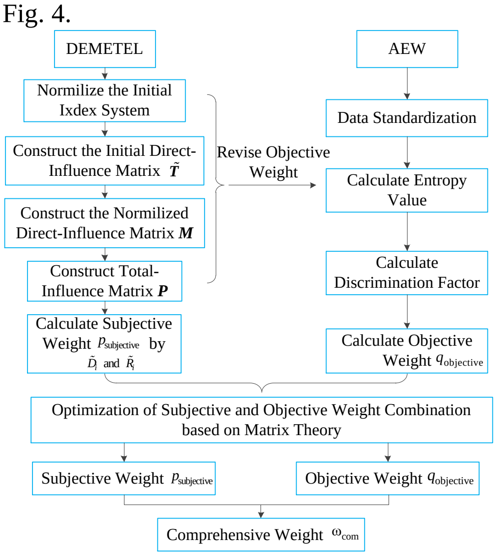

FIGURE 4. The progress of calculating comprehensive weights

A. FUZZY-DEMATEL TECHNIQUE FOR SUBJECTIVE WEIGHTS CALCULATION

It is worth noting that the DEMATEL has been widely used in power systems as a technique for assessing and selecting critical power system components against a set of selected criteria. The application of the Fuzzy-DEMATEL can mitigate the interference caused by objective factors in the assessment process. Therefore, this is the appropriate method for this evaluation research.

Step 1: Normalize the initial index system

Assume that a data matrix is configured as $\boldsymbol{X}_i = [\boldsymbol{x}_{ij}]_{n*m}$, where x_{ij} denotes the observed value of the j^{th} alternative for the i^{th} index, then the dimensionless value of x_{ij} is defined as:

$$x_{ij}^* = \begin{cases} x_{ij} \Big/ \sqrt{\sum_{i=1}^{n} x_{ij}^2} & (a) \\ \sqrt{\sum_{i=1}^{n} x_{ij}^2} \Big/ x_{ij} & (b) \end{cases} \tag{29}$$

where $i = 1, 2, 3, \dots, n$, $j = 1, 2, 3, \dots, m$, $x_{ij} \geq 0$, $x_{ij} \in (0,1)$, and $\sum_{i}^{n} \left(x_{ij}^*\right)^2 = 1$. For a benefit-type index, we use refer to (29a) to normalize the initial index and refer to (29b) to normalize the cost-type index.

Step 2: construct the initial direct-influence matrix $\tilde{\boldsymbol{T}}$

Based on the corresponding TFN shown in Fig. 5, we obtain the comparison result of the direct effect indexes $t_{ij}^k = \left(t_{ijk}^L, t_{ijk}^M, t_{ijk}^H\right)$ that C_i on C_j by expert k.

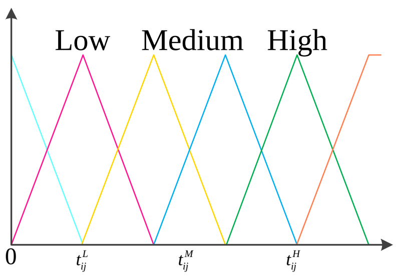

FIGURE 5. Distributions of a TFN, defined as the triplet $t_{ij}^k = \left(t_{ijk}^L, t_{ijk}^M, t_{ijk}^H\right)$

$$t_{ij}^k = \begin{cases} 0, & x_{ij} > t_{ijk}^L \\ \dfrac{x_{ij} - t_{ijk}^L}{t_{ijk}^M - t_{ijk}^L}, & t_{ijk}^L \le x_{ij} \le t_{ijk}^M \\ \dfrac{t_{ijk}^H - x_{ij}}{t_{ijk}^H - t_{ijk}^M}, & t_{ijk}^M \le x_{ij} \le t_{ijk}^H \\ 0, & x_{ij} > t_{ijk}^H \end{cases} \tag{30}$$

TABLE II
DEFINED LINGUISTIC VARIABLES AND HOMOLOGOUS TFNS

Linguistic variables	Abbreviations	Triangular fuzzy number (TFN)
No Influence	NI	0
Low Influence	LI	1
Medium Influence	MI	2
High Influence	HI	3
Very High Influence	VH	4

From the definition of refer to (30), we can know the diagonal element values of matrix $\boldsymbol{T}$ should be zero. The initial direct influence averages matrix $\tilde{\boldsymbol{T}}$ can be generated as:

$$t_{ij} = \left(t_{ij}^1 \oplus t_{ij}^2 \oplus \ldots \oplus t_{ij}^k\right) / k \tag{31}$$

$$\tilde{T} = \begin{bmatrix} 0 & t_{12} & \cdots & t_{1n} \\ t_{21} & 0 & \cdots & t_{2n} \\ \cdots & \cdots & 0 & \cdots \\ t_{n1} & t_{n2} & \cdots & 0 \end{bmatrix} \tag{32}$$

Step 3: Calculate the normalized direct-influence matrix ***M***

Matrix $\boldsymbol{M}$ can be derived using the following operations:

$$\tilde{m}_{ij} = t_{ij} / s \tag{33}$$

$$s = \max_{1 \le i \le n}\left(\sum_{j=1}^{n} t_{ij}^k\right) \tag{34}$$

Step 4: calculate total-influence matrix ***P***

According to refer to (35), we can calculate the matrix $\boldsymbol{P}$ as follows:

$$\tilde{P} = \lim_{k \to \infty}\left(\tilde{M} \oplus \tilde{M}^2 \oplus \ldots \oplus \tilde{M}^k\right) = \tilde{M}(I - \tilde{M})^{-1} \tag{35}$$

where $\boldsymbol{I}$ denotes a square ($n \times n$) matrix having ones on its diagonal.

Step 5: Determine Subjective weights by calculating $\tilde{D}_i$ *and* $\tilde{R}_i$

The sum of rows and columns obtained from matrix $\boldsymbol{P}$ are respectively expressed as $\tilde{D}_i$ and $\tilde{R}_i$. After that, the two variables $\left(\tilde{D}_i + \tilde{R}_i\right)$ and $\left(\tilde{D}_i - \tilde{R}_i\right)$ are calculated with ordered pairs of ($\tilde{D}_i + \tilde{R}_i$, $\tilde{D}_i - \tilde{R}_i$) as:

$$\tilde{D} = \left(\tilde{D}_i\right)_{n \times 1} = \left[\sum_{j=1}^{n} \tilde{p}_{ij}\right]_{n \times 1} \tag{36}$$

$$\tilde{R} = \left(\tilde{R}_j\right)_{1 \times n} = \left[\sum_{i=1}^{n} \tilde{p}_{ij}\right]_{1 \times n} \tag{37}$$

The relative, subjective importance of each criterion can be derived by:

$$P_{i0} = \left[\left(D_i + R_i\right)^2 + \left(D_i - R_i\right)^2\right]^{1/2} \tag{38}$$

Therefore, the subjective weight of the direct-influence relationship can be obtained by:

$$p_{(\text{subjective})\, j} = p_{i0} \Big/ \sum_{i=1}^{n} p_{i0} \tag{39}$$

B. ANTI-ENTROPY WEIGHTING (AEW) METHOD FOR OBJECTIVE WEIGHTS CALCULATION

Step 1: Calculate the probability of indexes using the AEW method

Define a sequence $x_{ij} = \left\{x_{1j}, x_{2j}, x_{3j}, \cdots x_{nj}\right\}$, $x_{ij} \ge 0$, which denotes the observed value of the j^{th} alternative for the i^{th} index, and the probability of x_{ij} is defined as:

$$\text{Pro}\left(x_{ij}\right) = x_{ij} \Big/ \sum_{i=1}^{n} x_{ij} \tag{40}$$

where i=1, 2, 3, …, n, and j=1, 2, 3, …, m.

Step 2: Calculate entropy value

Based on the first step, the entropy value of the j^{th} alternative is defined as:

$$e_j = -k\sum_{i=1}^{n} \text{Pro}\left(x_{ij}\right) \ln \text{Pro}\left(x_{ij}\right) = -\frac{1}{\ln n}\sum_{i=1}^{n} \text{Pro}\left(x_{ij}\right) \ln \text{Pro}\left(x_{ij}\right) \tag{41}$$

Step 3: Calculate the discrimination factor

The discrimination factor of the j^{th} alternative is defined as:

$$g_j = 1 - e_j \tag{42}$$

Step 4: Calculate the objective weight based on AEW method

The objective weight of the j^{th} alternative to the system is defined as:

$$q_{(\text{objective})\, j} = g_j \Big/ \sum_{j=1}^{m} g_j \tag{43}$$

Note that the amount of information that can be provided by an index, increases with a decrease in entropy; thus, the greater importance the index has, the greater the corresponding objective weight is.

C. COMPREHENSIVE WEIGHT CALCULATION

Since the importance of the two weights is different, this paper calculates the comprehensive weights based on the matrix theory. The objective and subjective weight relationship

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coefficients of each indexes ε_j and δ_j are calculated using the matrix theory as follows:

$$\begin{cases} \varepsilon_j = \dfrac{p_{(\text{subjective})j}}{p_{(\text{subjective})j} + q_{(\text{objective})j}} \\ \delta_j = \dfrac{q_{(\text{objective})j}}{p_{(\text{subjective})j} + q_{(\text{objective})j}} \end{cases} \quad 1 \le j \le m \tag{44}$$

where m denotes the dimension of the normalized eigenvector.

The final comprehensive weights are calculated by:

$$\omega_{\text{com}} = \frac{\varepsilon_j p_{(\text{subjective})j} + \delta_j q_{(\text{objective})j}}{\sum_{i=1}^{n} \left(\varepsilon_j p_{(\text{subjective})j} + \delta_j q_{(\text{objective})j} \right)} \quad 1 \le j \le m \tag{45}$$

D. COMPREHENSIVE SYSTEM COMPONENT RANKING BY VIKOR

The VIKOR was first introduced by Serafim Opricovic in 1998, and it is a multi-criteria optimization method based on the closeness between the evaluation value of each alternative and the ideal solution [22]. The steps of VIKOR are as follows:

Step 1: Calculation of positive and negative ideal solutions: Constructed the decision matrix $\boldsymbol{X}_i = [\boldsymbol{x}_{ij}]_{n*m}$, and determine positive ideal solutions x_i^+ and negative ideal solutions x_i^- of all the criterion indexes, j=1, 2, ..., m:

$$\begin{cases} x_i^+ = \max\limits_{1 \le j \le m} x_{ij} \\ x_i^- = \min\limits_{1 \le j \le m} x_{ij} \end{cases} \tag{46}$$

For benefit type, and

$$\begin{cases} x_i^+ = \min\limits_{1 \le j \le m} x_{ij} \\ x_i^- = \max\limits_{1 \le j \le m} x_{ij} \end{cases} \tag{47}$$

For cost type.

Step 2: Determination of utility and regret measures: Compute S_j (group utility) and R_j (individual regret) for each system by:

$$\begin{cases} S_j = \sum_{i}^{n} \omega_{com} \dfrac{x_i^+ - x_{ij}}{x_i^+ - x_i^-} \\ R_j = \max\limits_{1 \le i \le n} \omega_{com} \dfrac{x_i^+ - x_{ij}}{x_i^+ - x_i^-} \end{cases} \tag{48}$$

Step 3: Calculation of the VIKOR index: Compute the VIKOR index Q_j, j = 1, 2, ..., m, as follows:

$$Q_j = v \frac{S_j - S_j^-}{S_j^* - S_j^-} + (1 - v) \frac{R_j - R_j^-}{R_j^* - R_j^-} \tag{49}$$

where

$$S_j^* = \max_{1 \le j \le m} S_j ,\ S_j^- = \min_{1 \le j \le m} S_j \tag{50}$$

$$R_j^* = \max_{1 \le j \le m} R_j ,\ R_j^- = \min_{1 \le j \le m} R_j \tag{51}$$

and v denotes the weight of the strategy of the maximum group utility (0<v<1), and v is usually set to 0.5, whereas (1-v) is the weight of the individual regret.

Step 4: Calculation of VIKOR index: The alternatives are ranked decreasingly by the values S_j, R_j and Q_j. The results are three ranking lists.

Step 5: Finding of compromise solution: An alternative α_1, which is the best ranked by the measure $Q_{\max}$, is proposed as a compromise solution if the following two conditions are satisfied:

Condition 1: Acceptable advantage:

$$Q_{\alpha_2} - Q_{\alpha_1} \ge \frac{1}{m-1} \tag{52}$$

where α_2 represents the second best-ranked alternative by the measure Q, and m denotes the number of alternative solutions.

Condition 2: Acceptable stability in decision making: The alternative α_1 also has to be best-ranked by the measures S and or/ R. This compromise solution is stable within a decision-making process, which can be one of the following strategies: (i) maximum group utility (v>0.5), (ii) consensus (v ≈ 0.5), or (iii) veto (v<0.5).

If one of the conditions is not satisfied, then a set of compromise solutions is proposed, which consists of:

– Alternatives α_1 and α_2 if only Condition 2 is not satisfied.
– Alternatives α_1, α_2,... , α_k if Condition 1 is not satisfied; α_k is determined by the relation $Q_{\alpha_k} - Q_{\alpha_1} < \frac{1}{m-1}$ for a maximum k (the positions of these alternative solutions are "in closeness").

E. HYBRID FUZZY-DEMATEL-AEW-VIKOR METHOD

This paper mainly aims to evaluate and compare the SP and RE-CCHP systems from four different aspects using the hybrid MCDM approach Fuzzy-DEMATEL-AEW-VIKOR method. The fuzzy set is employed to deal with vague preference and opinions of experts, and the fuzzy operator is used to obtain the fuzzy average evaluation matrix. The comprehensive criteria's weights are adopted form the subjective and objective perspectives by average weighting operation, which is combined with the Fuzzy-TOPSIS. The impacts on multi-criteria are taken into account by employing the DEMATEL method, and subjective weighs of criteria are calculated as well. The AEW technique is used to calculate the objective weighs based on the specific performance data. Finally, after establishing the index system and determining its value and weight, a pure real multivariate function is constructed by the weighted average method to weigh the comprehensive performance level of the evaluation scheme. The aforementioned integration of the hybrid method is presented in Fig. 6.

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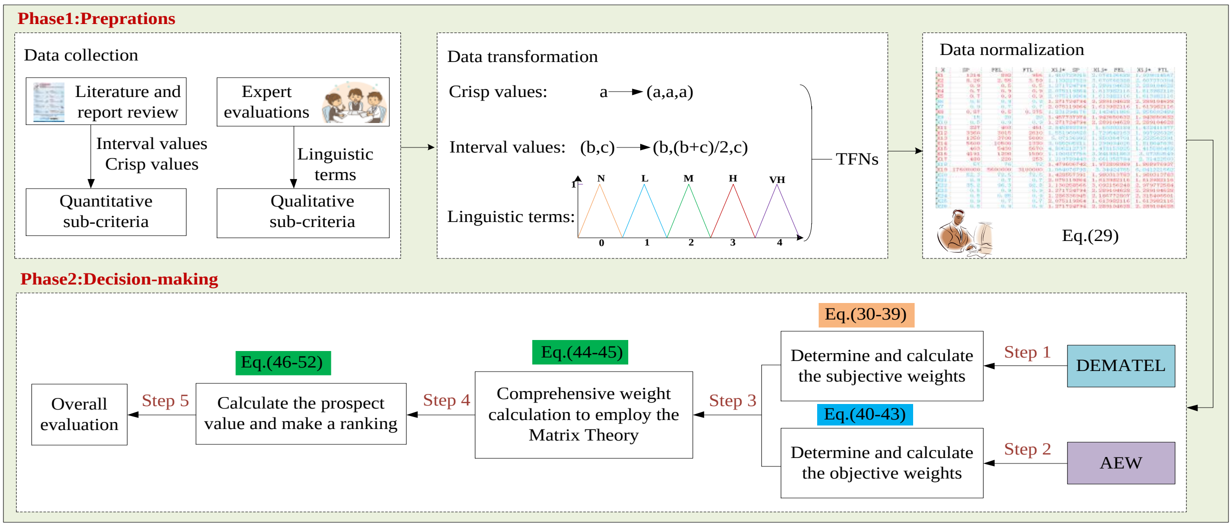

FIGURE 6. The decision framework of the Fuzzy-DEMATEL-AEW-VIKOR method

V. CASE STUDY

A. INTRODUCTION INTO RE-CCHP SYSTEM

At present, energy consumption in China is mainly based on fossil fuels, and the existing energy structure is not reasonable. In order to achieve energy sustainable development, the goal of energy saving, emission reduction, and large-scale utilization and development of the RE has become more important than before. Western China belongs to the arid continental climate of the middle temperate zone. Hence, the temperature difference between the four seasons is clear. Therefore, the combination of a CCHP system with RE energy can improve the discontinuity and instability of RE energy. The natural and weather conditions provide a basis for the application of a RE-CCHP system in western China [25]. The typical output curve of wind and PV energy in western China are shown in Fig. 7 and Fig. 8.

These distributed energy resources have obvious characteristics of stochastic, intermittent, and distributed dispersion. For instance, the operation characteristics of PV power plants are affected by the intensity of sunlight radiation, and PV power cannot operate at night. Also, wind power is affected by wind speed, and its output is usually smaller during the day than the night. Wind speed is faster during autumn, winter, and spring than in summer, and it is inversely proportional to the PV irradiation [25].

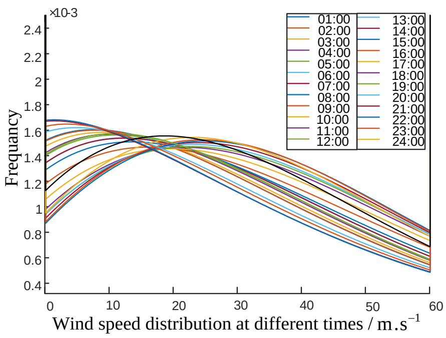

FIGURE 7. Wind energy output in western China

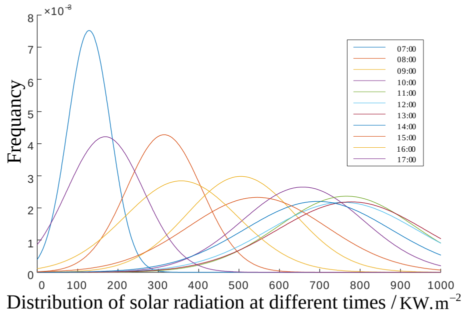

FIGURE 8. PV energy output in western China

B. BUILDING DESCRIPTION AND ENERGY DEMANDS

In order to verify the superiority over the RE-CCHP system than CCHP system and SP system, we find out the optimal operation strategy of RE-CCHP system and take into account the conditions of landscape resources and urban economic development of western China. This paper hypothetical chooses a 15-story building in a western city as the research object, which has a building area of 23300 m^2, and an average main ceiling height of 3.6 m. The total area of the window and glazing comprises 45% of the total wall area. The building operates during the entire year and it is temperature set around 22–25°C [25]. The specific area of the functional area required by the building and the required energy supply time are given in Table III.

TABLE III
THE FUNCTION AREA AND FUNCTION PLAN TIME OF THE STUDIED BUILDING

Building regional Classification	Building Area/m^2	Average energy Supply time per day/h
Lobby	800	24
Restaurant(meeting)	3000	10
Guest room	14200	20
Public area	5300	10

The monthly energy consumption of the RE-CCHP system load of the building is estimated using the software DeST, as shown in Fig. 9. It can be seen that the building's demand for cooling, heating, and power supply is basically

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the same, and has a strong regularity. The demand for domestic hot water is higher, because hot water is less affected by seasonal weather changes, and there is a demand for hot water use during all the seasons. The basic electricity load of the building is stable during the whole year [27].

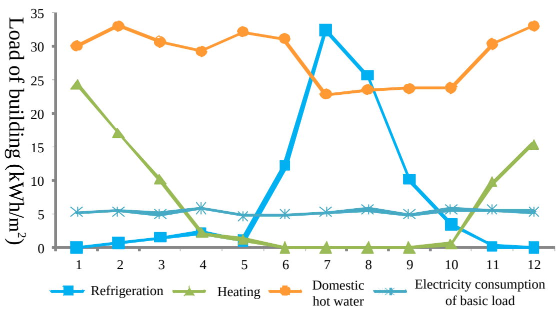

FIGURE 9. **Monthly average energy consumption per unit area of the studied building**

C. CALCULATION AND ANALYSIS OF RE-CCHP SYSTEM INDEX WEIGHT

The indexes of the RE-CCHP system are presented in Fig. 3, and the results are presented in Fig. 10.

Attributive Index	Index	SP	FEL	FTL
Environmental Attribute/P_1	X_1	1314	892	959
	X_2	8.26	2.55	3.56
	X_3	High	Low	Low
	X_4	Mid	High	High
	X_5	Mid	High	High
Social Attribute/P_2	X_6	Low	High	High
	X_7	High	Mid	Mid
	X_8	0.87	0.5	0.375
	X_9	15	20	20
	X_{10}	Low	High	High
Economical Attribute/P_3	X_{11}	227	403	451
	X_{12}	3360	3015	2650
	X_{13}	1350	3700	5600
	X_{14}	5600	13300	9500
	X_{15}	403	5430	5670
	X_{16}	4191	1200	1500
	X_{17}	480	220	253
	X_{18}	57	76	72
Technical Attribute/P_4	X_{19}	17600000	5600000	4300000
	X_{20}	52.3	72.5	72.5
	X_{21}	High	Mid	Mid
	X_{22}	35.2	96.3	92.8
	X_{23}	Low	High	High
	X_{24}	Low	High	High
	X_{25}	High	Mid	Mid
	X_{26}	Low	High	Mid

FIGURE 10. **The evaluation indexes' values of the RE-CCHP system**

After the index system was established, the weight of each index was calculated by using the Fuzzy-DEMATEL method. Firstly, the qualitative indexes of each scheme were quantified by using the fuzzy trigonometric function. After quantifying the qualitative indexes, quantified indexes were standardized. However, refer to (29b) was used to convert all the cost-type indexes into the benefit-type indexes, that is, the higher calculation results of indexes were, the better benefit of indexes was. At the same time, the DEMATEL was used to determine the weight to the overall evaluation of the attribute layer, and the judgment matrix ***A*** of the target layer was obtained.

$$P=\begin{bmatrix} 0 & 3 & 4 & 1 \\ 4 & 0 & 3 & 1 \\ 4 & 3 & 0 & 2 \\ 3 & 3 & 3 & 0 \end{bmatrix}$$

After normalization and consistency test, the subjective weight vector of attribute layer shown in Fig. 11. It can be seen that energy efficiency technical indexes were the most important in the attribute layer, followed by the environmental indexes, while the social attributes of indexes were less important than others.

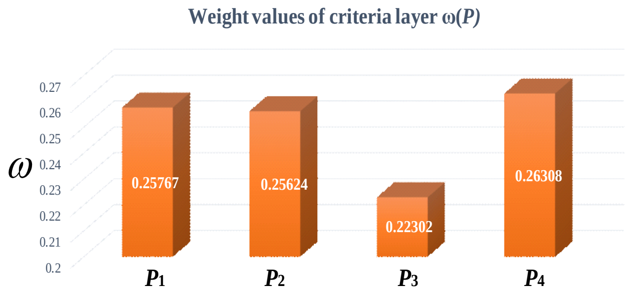

FIGURE 11. **The subjective weight vector of attribute layer**

Secondly, the judgment matrix of each attribute layer and index layer was calculated, that is, the judgment matrix $\boldsymbol{A_1}$ from P_1 layer to X_i layer, the judgment matrix $\boldsymbol{A_2}$ from P_2 layer to X_i layer, the judgment matrix $\boldsymbol{A_3}$ from P_3 layer to X_i layer, and the judgment matrix $\boldsymbol{A_4}$ from P_4 layer to X_i layer, were calculated. The results shown in Fig. 12 respectively.

$$A_1=\begin{bmatrix} 0 & 3 & 4 & 1 & 1 \\ 4 & 0 & 3 & 1 & 1 \\ 4 & 3 & 0 & 2 & 1 \\ 3 & 3 & 3 & 0 & 2 \\ 2 & 2 & 2 & 2 & 0 \end{bmatrix} \quad A_2=\begin{bmatrix} 0 & 2 & 3 & 2 & 4 \\ 3 & 0 & 3 & 1 & 2 \\ 3 & 4 & 0 & 1 & 1 \\ 3 & 1 & 1 & 0 & 2 \\ 4 & 3 & 1 & 2 & 0 \end{bmatrix}$$

$$A_3=\begin{bmatrix} 0 & 4 & 2 & 2 & 3 & 3 & 2 & 1 \\ 4 & 0 & 2 & 2 & 4 & 4 & 3 & 1 \\ 1 & 1 & 0 & 0 & 1 & 1 & 0 & 1 \\ 1 & 1 & 1 & 0 & 1 & 0 & 0 & 1 \\ 3 & 3 & 0 & 0 & 0 & 2 & 2 & 0 \\ 3 & 3 & 0 & 0 & 2 & 0 & 3 & 0 \\ 3 & 3 & 0 & 0 & 2 & 2 & 0 & 0 \\ 1 & 2 & 2 & 1 & 0 & 0 & 1 & 0 \end{bmatrix} \quad A_4=\begin{bmatrix} 0 & 4 & 2 & 3 & 1 & 0 & 1 & 0 \\ 3 & 0 & 2 & 4 & 2 & 3 & 3 & 1 \\ 1 & 1 & 0 & 2 & 3 & 1 & 4 & 1 \\ 2 & 4 & 2 & 0 & 3 & 3 & 2 & 1 \\ 2 & 2 & 3 & 2 & 0 & 2 & 2 & 2 \\ 2 & 3 & 2 & 2 & 2 & 0 & 2 & 2 \\ 2 & 2 & 4 & 1 & 2 & 0 & 0 & 1 \\ 2 & 2 & 0 & 1 & 1 & 1 & 1 & 0 \end{bmatrix}$$

FIGURE 12. **The judgment matrix of each attribute layer and index layer in RE-CCHP system**

After single ranking, normalization, and consistency test, the subjective weight vectors of index layer of RE-CCHP were obtained as follows: $p_{(subjective)j}$ = [0.06001, 0.05421, 0.05938, 0.04719, 0.03687, 0.06293, 0.05264, 0.04882, 0.03826, 0.05358, 0.04127, 0.04506, 0.01512, 0.01302, 0.03235, 0.03259, 0.02974, 0.01386, 0.03115, 0.04186, 0.03386, 0.03880, 0.03442, 0.03074, 0.03269, 0.01958]. The subjective weights of three cases are shown in Fig. 13.

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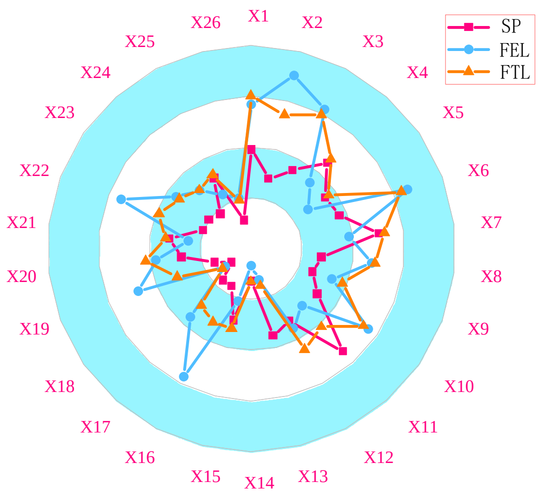


FIGURE 13. The subjective weight vectors of index layer

Thirdly, the AEW method was used to obtain the objective weight matrix as follows, and then the comprehensive weights of the index system were obtained, and they are given by Fig. 14 and shown in Fig. 15.

$q_{(objective)j}=$

0.03888	0.03892	0.03752
0.03673	0.03991	0.03891
0.03725	0.03908	0.03918
0.03851	0.03841	0.03846
0.03851	0.03841	0.03846
0.03731	0.03908	0.03911
0.03859	0.03839	0.03839
0.03708	0.03883	0.03963
0.03747	0.03887	0.03915
0.03731	0.03908	0.03911
0.04089	0.03776	0.03646
0.03977	0.03810	0.03736
0.04396	0.03719	0.03358
0.03925	0.03354	0.04269
0.04778	0.03417	0.03242
0.03686	0.04047	0.03817
0.03770	0.03952	0.03822
0.03741	0.03892	0.03917
0.03569	0.03914	0.04088
0.03734	0.03891	0.03927
0.03859	0.03839	0.03839
0.03655	0.03937	0.03968
0.03731	0.03908	0.03911
0.03736	0.03899	0.03916
0.03859	0.03839	0.03839
0.03731	0.03809	0.03911

$\omega_{com}=$

0.04978	0.05006	0.04959
0.04539	0.04662	0.04617
0.04896	0.04969	0.04959
0.04168	0.04187	0.04178
0.03631	0.03646	0.03639
0.05141	0.05208	0.05195
0.04496	0.04514	0.04503
0.04213	0.04298	0.04317
0.03646	0.03734	0.03738
0.04515	0.04595	0.04584
0.03955	0.03833	0.03767
0.04100	0.04054	0.04014
0.03522	0.02983	0.02689
0.03149	0.02692	0.03453
0.04000	0.03222	0.03128
0.03356	0.03578	0.03438
0.03292	0.03419	0.03332
0.02989	0.03131	0.03144
0.03223	0.03447	0.03541
0.03825	0.03915	0.03921
0.03502	0.03511	0.03502
0.03630	0.03784	0.03789
0.03458	0.03572	0.03565
0.03309	0.03422	0.03424
0.03455	0.03463	0.03454
0.03005	0.03153	0.03148

FIGURE 14. The objective weight matrix and the comprehensive weight matrix of RE-CCHP system

According to the Fig. 14 and Fig. 15, the occupied space of the CO_2 emission index, social benefit index, annual operation cost index and primary energy utilization index of the RE-CCHP system had the highest weights among the four attributes (environment attribute, social attribute, economic attribute, and energy efficiency technical attribute), which need to be studied emphatically.

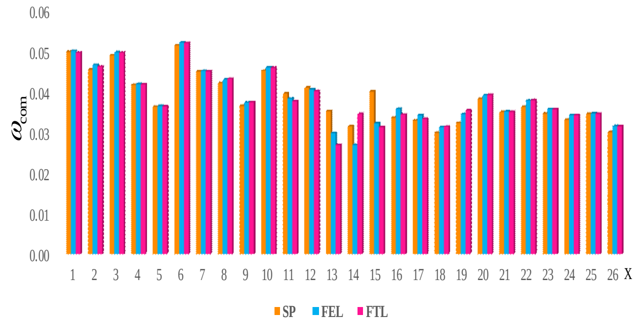


FIGURE 15. Comprehensive weights of indexes of the RE-CCHP system

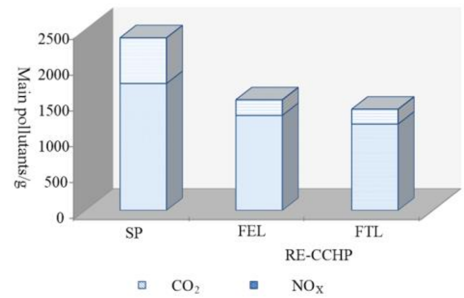
Lastly, it can be seen that although the economic cost of the RE-CCHP system was greater than that of the SP system, the efficiency of the combined system was better than that of the SP system in environmental protection, society, and energy efficiency technology.

VI. THE KEY INDEXES COMPARISON OF SP AND RE-CCHP SYSTEMS

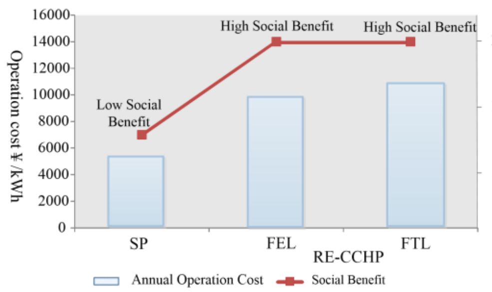
To quantifying the benefits achieved by using the RE-CCHP system over the reference SP system, the evaluation criteria were formulated.

A. *OVERALL EVALUATION*

The key indexes comparison of each attribute layer of the RE-CCHP systems in the FEL and FTL modes and SP system shown in Fig. 16.



(a) Comparison of key indexes of environmental attributes



(b) Comparison of key indexes of economic and social attributes

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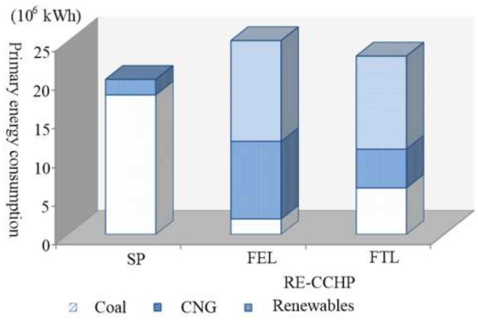

(c) Comparison of key indexes of technical attributes

FIGURE 16. The key indexes analysis of the SP and RE-CCHP systems

Fig. (16a) shows that the emission of environmental pollutants (CO_2, NO_X) of the SP system was higher than that of the RE-CCHP system, while the emission of pollutants of the RE-CCHP system was the smallest when it operated in the FTL mode. Fig. (16b) compares the key indexes of the SP and RE-CCHP systems from the economic and social aspects. In terms of economy, the RE -CCHP system was uneconomical. This was due to the addition of the wind and PV power generating units to the CCHP system. The installation cost and operation and maintenance cost were higher, so the overall cost was higher than those of the SP system, but on the other hand, the social benefits of the RE-CCHP system were much better than that of the SP system. As shown in Fig. (16c), the SP system consumed the most fossil-fuel resources while the natural gas consumption ranked in the opposite order. In addition, the energy consumption of the FEL mode of the RE-CCHP system was about 5% higher than that of the FTL mode. In general, RE-CCHP system superior to the SP system Because of the maximum solar energy utilization.

From the four aspects of the environment, society, economy, and technology, it was found that although the economic cost of the RE-CCHP system was greater than that of the SP system, the benefits in environmental protection, society, and technology of the RE-CCHP system were superior over those of the SP system.

B. COMPARISON OF COMPREHENSIVE PERFORMANCE OF RE-CCHP SYSTEM UNDER DIFFERENT OPERATION STRATEGIES

This section furthers analyzes the RE-CCHP system performance under the FTL and FEL operation modes for 12 months. According to Section V, after establishing the index system and determining its value and comprehensive weight, the comprehensive performance of the FTL and FEL modes under four attribute levels can be evaluated by comparing them. The comprehensive performance evaluation values of the RE-CCHP system under the two operation modes were obtained, and they are shown in Fig. 17.

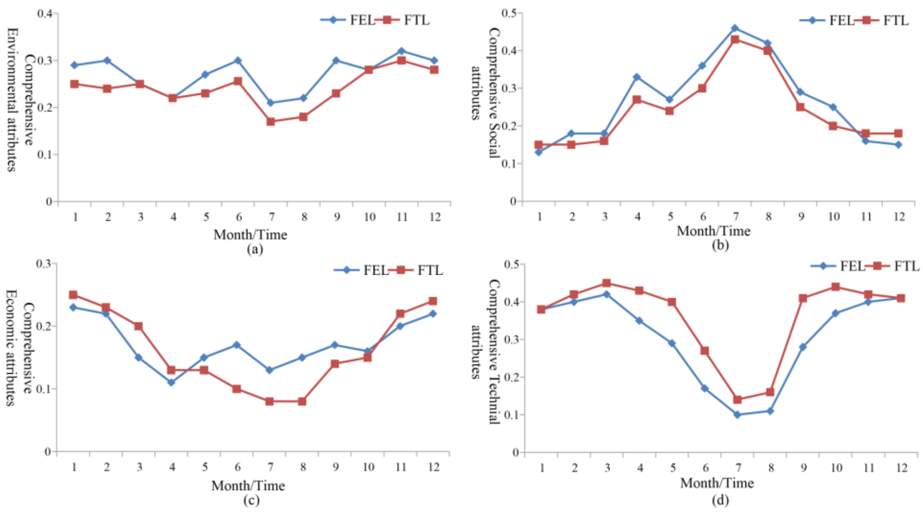

FIGURE 17. The comparison of different indexes under the FET and FTL modes

As can be seen in Fig. (17a), the comprehensive index value of the environmental attributes of the RE-CCHP system under the FEL mode was higher than that under the FTL mode during the whole year, but the two trends were consistent. Compared with the FTL mode, the annual fluctuation range of comprehensive environmental indexes of the FEL mode was relatively small. In Fig. (17b), it can be seen that the monthly operation performance of the RE-CCHP system was better in summer than in winter, and the comprehensive index value of the social attribute under the FEL mode was higher than under the FTL mode. The monthly performance trend of the RE-CCHP system displayed in Fig. (17c) is contrary to than in Fig. (17b). The overall performance of the RE-CCHP system was better in winter than in summer. The economy of the FEL mode was better than of the FTL mode in winter, while in the other seasons, the economy of the FTL mode was slightly better than of the FEL mode; thus, it can be concluded that the FTL mode is not suitable for the whole year operation of the RE-CCHP system. Fig. (17d) shows that the trend of technical energy consumption index of the RE-CCHP system was the same in all the months of the year under both operation modes. Energy saving of the FTL mode was better than of the FEL mode, and the technical energy consumption index of the RE-CCHP system was the lowest in summer.

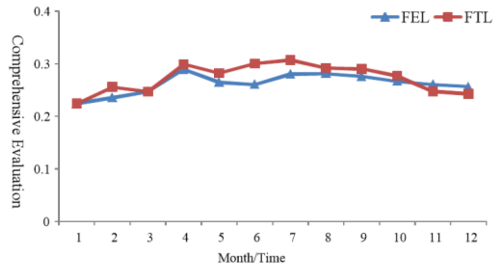

FIGURE 18. Comprehensive performance evaluation between FET and FTL system

Finally, the comprehensive performance evaluation values of the cogeneration system under the two operation strategies are obtained by using the weighted average method, as shown in Fig. 18. In general, although the comprehensive evaluation values of environmental protection, society and economy of FTL mode are slightly higher than FEL mode, the comprehensive evaluation values of energy technology of FTL mode are higher than FEL mode. According to the calculation results in Section ***A***, the technical indicators account for the highest proportion in terms of the other three indicators. FTL mode of RE-CCHP system can improve the energy utilization rate, and make full use of energy resources can bring the best economic benefits. Therefore, its comprehensive performance is better than FEL mode.

C. FILE FORMATS FOR GRAPHICS

A sensitivity analysis was carried out to test the robustness of the benefit assessment. Fig. 19 shows the cases where X_1 to X_{26} have ±10%, ±20%, and ±30% ranking of weight changes on the base comprehensive weight in Fig. 14. The result show that when the weights of the 26 criteria change within the range of ±10%, ±20%, and ±30%, the evaluation ranking results is always stable. This demonstrates that the Fuzzy-DEMATEL-AEW algorithm is robust and credible.

VII. COMPREHENSIVE PERFORMANCE EVALUATION OF RE-CCHP SYSTEM BY VIKOR

After obtaining the comprehensive weights of all the indexes, the next step was to rank the systems on the basis of these indexes' comprehensive weights using the VIKOR method. According to refer to (29), the standardized index matrix $\boldsymbol{X}_i = [\boldsymbol{x}_{ij}]_{n*m}$ was established. Also, the maximum and minimum ideal values of the indexes were calculated using refer to (45) and (47), respectively. The calculation result matrix is given in Table IV. Further, using refer to (48) - (49), the values of S, R, and Q were calculated and ranked on the basis of Q values; the system, having the lowest Q values, was selected as the best system alternative to satisfying two conditions as mentioned in Step 5. Finally, the values and ranks of S, R, and Q were obtained, and they are given in Table V. The alternatives were arranged in descending order as follows: the FTL, the FEL, and the SP. The RE-CCHP system under the FTL mode obtained rank first as it had the lowest Q value, as shown in Table V.

TABLE IV
THE ORIGINAL MATRIX BY VIKOR

X	SP	FEL	FTL	x_i^+	x_i^-
X_1	1.41073	2.07814	1.93901	2.07814	1.41073
X_2	1.13323	3.67077	2.60737	3.67077	1.13323
X_3	1.27172	2.28910	2.28910	2.28910	1.27172
X_4	2.07512	1.61398	1.61398	2.07512	1.61398
X_5	2.07512	1.61398	1.61398	2.07512	1.61398
X_6	1.27172	2.28910	2.28910	2.28910	1.27172
X_7	2.07512	1.61398	1.61398	2.07512	1.61398
X_8	1.23129	2.14245	2.85660	2.85660	1.23129
X_9	1.45774	1.94365	1.94365	1.94365	1.45774
X_{10}	1.27172	2.28910	2.28910	2.28910	1.27172
X_{11}	2.84589	1.60302	1.43241	2.84589	1.43241
X_{12}	1.55196	1.72955	1.99793	1.99793	1.55196
X_{13}	5.07137	1.85036	1.22256	5.07137	1.22256
X_{14}	2.13823	1.14039	9.00308	9.00308	1.14039
X_{15}	19.50634	1.44771	1.38643	19.50634	1.38643
X_{16}	1.10004	3.84188	3.07351	3.84188	1.10004
X_{17}	1.21979	2.66136	2.31423	2.66136	1.21979
X_{18}	1.47961	1.97281	1.86898	1.97281	1.47961
X_{19}	1.06408	3.34425	6.04122	6.04122	1.06408
X_{20}	1.42856	1.98031	1.98031	1.98031	1.42856
X_{21}	2.07512	1.61398	1.61398	2.07512	1.61398
X_{22}	1.13026	3.09216	2.97977	3.09216	1.13026
X_{23}	1.27172	2.28910	2.28910	2.28910	1.27172
X_{24}	1.28634	2.18677	2.31541	2.31541	1.28634
X_{25}	2.07512	1.61398	1.61398	2.07512	1.61398
X_{26}	1.27172	2.28910	2.28910	2.28910	1.27172

TABLE V
SYSTEMS RANKING REGARDING *R*, *S* AND *Q* VALUES

Index	S_j^*	Rank	R_j	Rank	Q_j	Rank
SP	0.68872	3	0.05141	3	1	3
FEL	0.37716	2	0.04514	2	0.0558	2
FTL	0.34474	1	0.04503	1	0	1
	$S_j^* = 0.68872$			$R_j^* = 0.05141$		
	$S_j^- = 0.34474$			$R_j^- = 0.04503$		

TABLE VI
SENSITIVITY ANALYSIS

$Q(v)$	Alternatives SP	FEL	FTL	Ranking
$Q(v$=0)	1	0.01724	0	FTL>FEL>SP
$Q(v$=0.1)	1	0.02494	0	FTL>FEL>SP
$Q(v$=0.2)	1	0.03264	0	FTL>FEL>SP
$Q(v$=0.3)	1	0.04034	0	FTL>FEL>SP
$Q(v$=0.4)	1	0.04804	0	FTL>FEL>SP
$Q(v$=0.5)	1	0.05575	0	FTL>FEL>SP
$Q(v$=0.6)	1	0.06345	0	FTL>FEL>SP
$Q(v$=0.7)	1	0.07115	0	FTL>FEL>SP
$Q(v$=0.8)	1	0.07885	0	FTL>FEL>SP
$Q(v$=0.9)	1	0.08655	0	FTL>FEL>SP
$Q(v$=1)	1	0.09425	0	FTL>FEL>SP

On the basis of the previous analysis, the VIKOR comprehensive evaluation method was adopted to evaluate and rank the proposed system. As can be seen from the results presented in Table VI, the RE-CCHP system was superior to the SP system, and the FTL mode in the RE-CCHP system was superior to the FEL mode.

TABLE VII
COMPARISON OF THE RESULTS COMPUTED BY DIFFERENT EVALUATION METHODS

Methods	SP	FEL	FTL
VIKOR	1	0.05575	0
Direct evaluation method	0.580109	0.518005	0.48229

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Fuzzy comprehensive evaluation method	0.045469	0.045466	0.045226

Table VII shows that the results obtained by the VIKOR method were similar to those obtained by the Fuzzy comprehensive evaluation method and direct evaluation method. The order for alternative's advantages and disadvantages was the FTL, the FEL, and the SP. The direct evaluation method based on the product of the weight matrix and evaluation matrix had poor generality because it did not consider the relationship between the indexes. The fuzzy comprehensive evaluation method had a relatively solidified fuzzy distribution selection and poor objectivity. In conclusion, the VIKOR method proposed in this paper overcame the shortcomings of these fuzzy comprehensive evaluation method and direct evaluation method, and the evaluation effect was more reasonable.

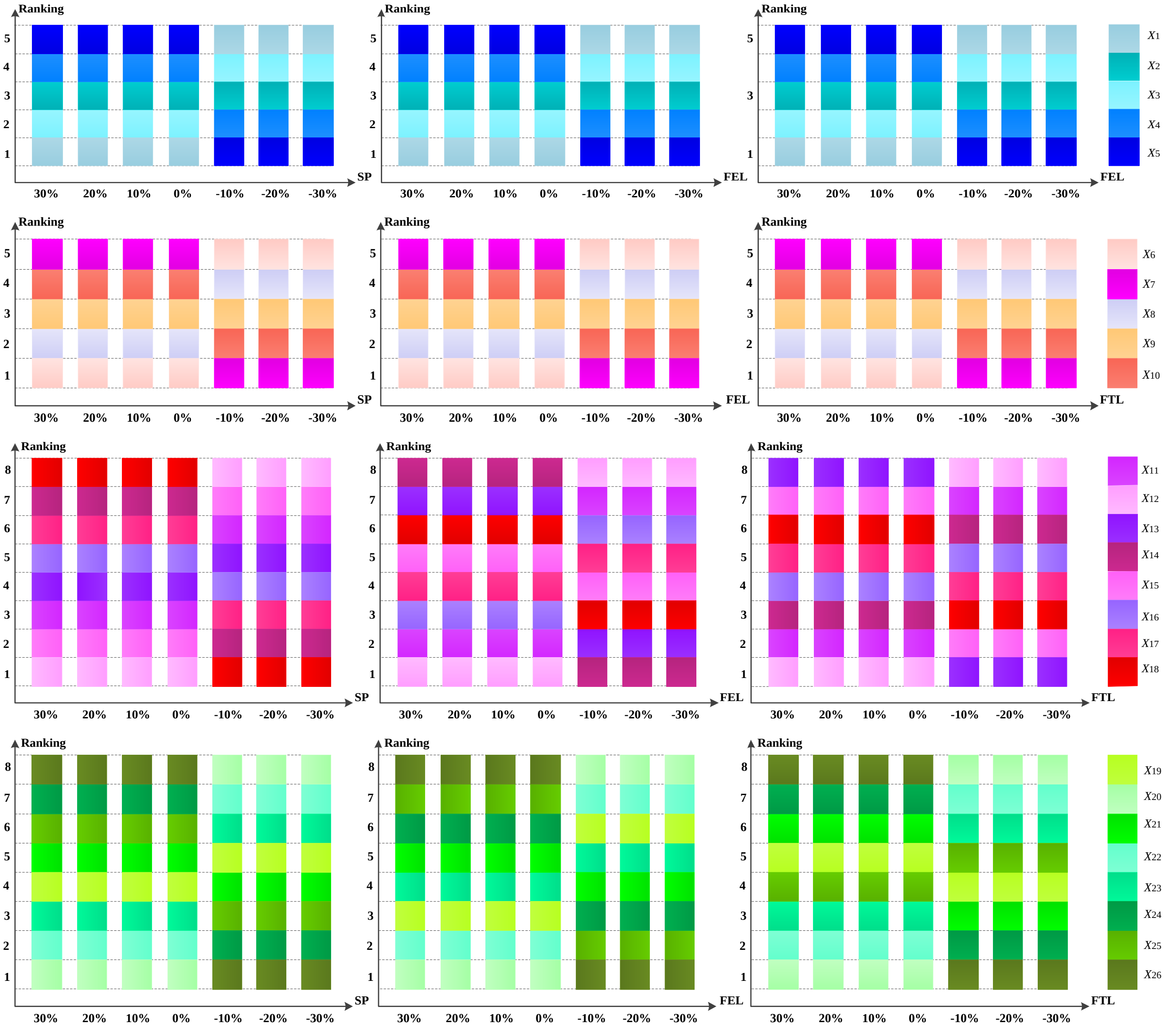

FIGURE 19. Ranking results of the sensitivity analysis

VIII. CONCLUSION

This paper proposes a comprehensive evaluation method of a RE-CCHP system based on the MCDM theory using the weight factor. A hierarchical RE-CCHP evaluation criteria framework is proposed and validated by experts. two MCDM weights decision methods, specifically the DEMATEL and the AEW, are combined with the matrix theory to calculate a set of multi-level criteria, which consists of four main attributes and twenty-six sub-criteria. An empirical case study on the RE-CCHP system using the building in western China is presented to demonstrate the proposed approach and rank the SP system and the two main controlling modes (FEL and FTL) of the RE-CCHP system by the VIKOR method. The results of the case study are verified by two different methods. In addition, a sensitivity analysis is also conducted to verify the robustness and effectiveness of the proposed weight calculation approach. Thus, the model not only can be compatible with different index systems but also can identify the RE-CCHP system's greater or weaker level of operation mode.

This paper aims to evaluations and denotes a supporting decision tool for investors, which originality in its comprehensive evaluation criteria structure, which is a comprehensive evaluation regarding the four attributes of the RE-CCHP system. In addition, to the best of authors' knowledge, the combination of the comprehensive weights calculation methods (DEMATEL and AEW, optimized by matrix theory) with the VIKOR method for ranking comparison between the SP and RE-CCHP systems has not been published in the literature yet. Replacing the traditional SP system with the RE-CCHP system can greatly reduce the consumption of fossil fuels and promote the utilization of renewable energy. Our future work will focus on how to use renewable energy efficiently, reduce costs and keep the energy sustainability.

DECLARATION OF COMPETING INTEREST

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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REFERENCES

[1] B. Zhang, et al, "Performance investigation of a new cooling, heating and power system with methanol decomposition based chemical recuperation process," Appl. Energy, vol. 229, pp. 1152–1163, 2018.

[2] M. Sheykhi, M. Chahartaghi, A. A. Safaei Pirooz, "Investigation of the effects of operating parameters of an internal combustion engine on the performance and fuel consumption of a CCHP system," Energy, vol. 211, pp. 119041, 2020. doi.org/10.1016/j.energy.2020.119041.

[3] F. Ren, Z. Wei, X. Zhai, "Multi-objective optimization and evaluation of hybrid CCHP systems for different building types," Energy, vol. 215, pp. 119096, 2021. doi.org/10.1016/j.energy.2020.119096.

[4] W. Di, Z. Jifeng, L. Zhijian, "Thermodynamic analyses and optimization of a novel CCHP system integrated organic Rankine cycle and solar thermal utilization," Energy Conversion and Management, vol.196, pp. 453-466, 2019.

[5] L. Long, Y. Shi, M. Hai, "Optimization and evaluation of CCHP systems considering incentive policies under different operation strategies," Energy, vol. 162, pp. 825–840, Nov. 2018. doi.org/10.1016/j.energy.2018.08.083.

[6] J. Wang, Z. Zhai, Y. Jing, "Optimization design of BCHP system to maximize to save energy and reduce environmental impact," Energy, vol. 35, no. 8, pp. 3388–3398, Jun. 2010. doi.org/10.1016/j.energy.2010.04.029.

[7] T. Jamal, T. Urmee, G.M. Shafiullah, "Planning of off-grid power supply systems in remote areas using multi-criteria decision analysis," Energy, vol. 201, pp. 117580, 2020. doi.org/10.1016/j.energy.2020.117580.

[8] M. Soltani, M. Chahartaghi, S. M. Hashemian, "Technical and economic evaluations of combined cooling, heating and power (CCHP) system with gas engine in commercial cold storages," Energy Conversion and Management," Energy, vol. 214, pp. 112877, 2020. doi.org/10.1016/j.enconman.2020.112877.

[9] L Zhang, J Chai, H Xin, "Evaluating the comprehensive benefit of hybrid energy system for ecological civilization construction in China," Journal of Cleaner Production, vol. 278, pp. 123769, 2021. doi.org/10.1016/j.jclepro.2020.123769.

[10] F. Le, D. Xiao, M. Jun, "Analysis of energy matching performance between CCHP systems and users based on different operation strategies," Energy Convers. and Manag., vol. 182, pp. 60–71, Feb. 2019. doi.org/10.1016/j.enconman.2018.12.006.

[11] L Kang, J Yang, Q An, "Complementary configuration and performance comparison of CCHP-ORC system with a ground source heat pump under three energy management modes," Energy Convers. and Manag., vol. 135, pp. 244-255, 2017.

[12] H Yousefi, MH Ghodusinejad, Y Noorollahi, "GA/AHP-based optimal design of a hybrid CCHP system considering economy, energy and emission," Energy Build, pp. 138:309–17, 2017.

[13] W. Jiang, J. You, Z. Chun, "Performance comparison of combined cooling heating and power system in different operation modes," Appl. Energy, vol. 88, no. 12, pp. 4621–4631, Dec. 2011. doi.org/10.1016/j.apenergy.2011.06.007.

[14] L. Li, S. Yu, H. Mu, H. Li, "Optimization and evaluation of CCHP systems considering incentive policies under different operation strategies," Energy, vol. 162, pp. 825-840, 2018. doi.org/10.1016/j.energy.2018.08.083.

[15] W. Jiang, Y. Yang, "Energy, exergy and environmental analysis of a hybrid combined cooling heating and power system utilizing biomass and PV energy," Energy Convers. Manag., vol. 124, pp. 566–577, 2016.

[16] S. Peng, S. He, Y. Dong, "Economic optimization and analysis on varied kinds of CCHP systems," Control Eng. of China, vol. 23, no.10, pp. 1584–1590, 2016.

[17] A. Sohani, S. Rezapour, H. Sayyaadi, "Comprehensive performance evaluation and demands' sensitivity analysis of different optimum sizing strategies for a combined cooling, heating, and power system," Journal of Cleaner Production, vol. 279, no. 10, pp. 123-225, Jan. 2021. doi.org/10.1016/j.jclepro.2020.123225

[18] K. Abhishek, S. Bikash, R. S. Arvind, "A review of multi criteria decision making (MCDM) towards sustainable renewable energy development," Renewable and Sustainable Energy Reviews, vol. 69, pp. 596–609, Mar. 2017. doi.org/10.1016/j.rser.2016.11.191.

[19] W. Zhen, X. Guang, W. Heng, "Distributed energy system for sustainability transition: A comprehensive assessment under uncertainties based on interval multi-criteria decision making method by coupling interval DEMATEL and interval VIKOR," Energy, vol. 169, pp. 750–761, Feb. 2019. doi.org/10.1016/j.energy.2018.12.105.

[20] Z. Fu, W. Xu, K. Ming, "Sustainable recycling partner selection using fuzzy DEMATEL-AEW-FVIKOR: A case study in small-and-medium enterprises (SMEs)," J. of Cleaner Produc., vol. 196, pp. 489–504, Sep. 2018.

[21] W. Peng, Z. Zhou, W. Yong, "A novel hybrid MCDM model combining the SAW, TOPSIS and GRA methods based on experimental design," Info. Sciences, vol. 345, pp. 27–45, 2016. doi.org/10.1016/j.ins.2016.01.076.

[22] T. Kaya, C. Kahraman, "Multicriteria renewable energy planning using an integrated fuzzy VIKOR & AHP methodology: the case of Istanbul," Energy, vol. 35, no. 6, pp. 2517–2527, Jun. 2010. doi.org/10.1016/j.energy.2010.02.051.

[23] M. Martín-Gamboa, D. Iribarren, D. García-Gusano, "A review of life-cycle approaches coupled with data envelopment analysis with in multi-criteria decision analysis for sustainability assessment of energy systems," J Clean Prod., vol. 150, pp. 164–174, May. 2017. //doi.org/10.1016/j.jclepro.2017.03.017.

[24] H. Ren, W. Gao, W. Zhou, "Multi-criteria evaluation for the optimal adoption of distributed residential energy systems in Japan," Energy Pol., vol. 37, no. 12, pp. 5484–5493, Dec. 2009. doi.org/10.1016/j.enpol.2009.08.014.

[25] J. Wu, S. Maihemuti, W. Wang, "Comprehensive Performance Evaluation and Research of RE-CCHP System," 2019 IEEE Innovative Smart Grid Technologies - Asia (ISGT Asia), Chengdu, China, pp. 1558-1563, 2019.
doi: 10.1109/ISGT-Asia.2019.8881334.

[26] X Kong, R Wang, X Huang, "Energy optimization model for a CCHP system with available gas turbines," Appl. Therm. Eng., vol. 25, no.2–3, pp. 377–391, 2005.

[27] F. Le, D. Xiao, M. Jun, "Analysis of energy matching performance between CCHP systems and users based on different operation strategies," Energy Convers. and Manag., vol. 182, pp. 60–71, Feb. 2019. doi.org/10.1016/j.enconman.2018.12.006.