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Analysis and evaluation of various energy technologies in seawater desalination

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ABSTRACT

At present, in addition to fossil energy and other conventional energy, the application of clean energy resources like wind energy, solar energy and nuclear energy in seawater desalination is rising around the word. It represents the future direction of desalination technology development, meeting the need of a resource-saving and environmentally-friendly society. And the technology has a great prospect of applying in regions in serious shortage of fresh water and energy. This paper concludes the advantages and disadvantages of various schemes by analyzing and comparing seawater desalination technologies of various energy. By analyzing five aspects including technological factor, environmental factor, social factor, economic factor and management factor, this paper proposes an evaluation indicators system of the application of energy technologies in seawater desalination. Evaluate the alternative schemes of the coupling of an island's seawater desalination project and energy technologies by fuzzy comprehensive evaluation based on Analytic Hierarchy Process (AHP) and select the optimal scheme. This method provides scientific evaluation methods for the application of energy technologies in seawater desalination.

Keywords: Energy technology; Seawater desalination; Evaluation

1. Introduction

Seawater desalination is an energy-intensive industry, which needs to consume large amounts of energy. The mostwidely used energy for seawater desalination now is coal, petroleum, natural gas and other conventional energy resources. Plenty of conventional energy consumption will increase environmental pollution and greenhouse gases, and it will also go against global environmental protection and sustainable development of ecology, putting great hidden dangers to the environment. That is why developing and utilizing new energy for seawater desalination is drawing more and more attention by the public. At present, the technology in new energy desalination has not been large-scale applied at home and abroad yet, but it represents the future direction of desalination technology development, meeting the need of a resource-saving and eco-friendly society. So the technology has a great prospect of applying in regions in serious shortage of fresh water and energy

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[1–3]. In order to push the application of new energy technologies in desalination forward, analyzing, and comparing the application of conventional energy and other energy technologies in desalination, finding out their respective strengths and weaknesses, combining with specific conditions and choosing one of the most appropriate energy technologies are necessary.

Firstly, the study of desalination technology has become increasingly common at present. The qualitative and quantitative analysis of the economic utility of desalination technology is particularly important at the same time, which can help select the most economical desalination technology to use the same cost. Many analyses of the economics of desalination technology applications only from the cost point of view, using economic cost analysis. Even a lot of articles analyzed the environmental, social, and other factors, these articles lack in specific quantitative analysis. Based on expert investigation method, Analytic Hierarchy Process (AHP) method, fuzzy evaluation theory, the paper builds a comprehensive evaluation system and use a quantitative evaluation method which is certain innovative in evaluation of the desalination scheme.

Secondly, it is not a long time that renewable energy technologies used in desalination. This paper has not only evaluation of traditional energy technologies in desalination but also evaluation of renewable energy technologies such as wind and solar energy in desalination. This paper selects objective indicators such as cost factors and subjective indicators such as social factors, uses AHP method and decides weights of indicators relying on experts' consistent opinion to the importance of indicators, then quantifies subjective opinions of experts by fuzzy comprehensive evaluation method, so it meets the requirements of combination of subjective and objective and that of qualitative and quantitative so as to obtain a more efficient result of evaluation.

Finally, viewing from the existing literature, there are many separate evaluation of coupling scheme of some kind of energy technologies and desalination, but there are few summary and comparison of these schemes. This paper not only compares the same energy technology scheme coupled by different desalination technologies, but also compares the same desalination technology scheme coupled by deferent energy technology. Furthermore, the results of the evaluation of all schemes were classified and compared. In particular, it compares the two power technologies schemes of grid power generation technology and independent power generation technology coupled by desalination, which makes the more detailed and in-depth results of evaluation.

2. Analyses of advantages and disadvantages of various energy technologies in seawater desalination

From the trend of the world's energy sources utilization, seawater desalination industry uses traditional fossil energy sources, as well as wind energy, solar energy, nuclear energy and other alternative energy sources.

2.1. Fossil energy

The project of fossil energy seawater desalination (Fossil energy seawater desalination project) mainly, provides power for seawater desalination after electrical power is generated by fossil energy resources. Fossil energy includes coal, petroleum, and natural gas. Currently, the most popular power generation technologies are pulverized fuel, fluidized bed combustion, integrated gasification combined cycle, steam turbine condensate, and gas steam combined cycle, and some other technologies. The major advantages of fossil energy desalination technology are mature, stable, strong competitiveness in the economy [4,5]. However, the main disadvantage of it is, as a kind of non-renewable energy, the energy security is greatly affected by international energy market, leading to temporary breach and a serious shortage of energy supply, or prices soaring, which will affect the stability and economy of production. In addition, excessive CO_2 emission of the fossil energy will also bring to environmental pollution and destruction, putting more on the shoulders of regional energy conservation and emission reduction.

2.2. Wind energy

Wind energy seawater desalination usually consists of wind electric desalination (separation) and wind-driven directly by seawater desalination (coupling). Separation type is to convert wind energy into electrical energy first and then drive the desalting unit to start the seawater desalination. Coupling type is to use the mechanical energy converted from wind energy to drive the desalting unit for seawater desalination. Both must adopt relevant adjusting device to solve the problem of the volatility of wind energy(fluctuation). Maritime wind resources are abundant, having characteristics of high wind speed and relative stability so wind energy is an important energy choice of seawater desalination [6,7]. The major advantages of the wind energy desalination projects are: first of all, CO_2

emission is low, which is 8∼30 g/kWh [4]. Secondly, in some regions with abundant wind energy resources but poor fresh water resources,wind energy desalination is able to operate independently, be combined randomly and be strongly adaptive, which is especially fit for isolated island areas away from the power grid of the mainland. The major disadvantages are: Firstly, the fluctuation of wind power may lead to a unstable fresh water production, which will result in having difficulties in guaranteeing a large scale of stable and reliable water supply for cities; Secondly, the unilateral cost of wind power seawater desalination is higher than coal-fired and nuclear desalination projects, so its economic efficiency is not so strong [8–13].

2.3. Solar energy

Solar seawater desalination can be divided into two categories. One is the direct method, and the other is the indirect method. The direct method is utilizing a device to integrate the power-concentration part (section) and the desalination part (section). The indirect method is utilizing a device to separate the power-concentration part and the desalination part. The direct method is to obtain freshwater from the evaporation and condensation of seawater, but it's efficiency is decreased due to covering too large area. The indirect method mainly consists of solar distillation seawater desalination and solar reverse osmosis seawater desalination. Solar distillation seawater desalination is gathering up thin and low-density solar energy as heat sources to provide energy for the system. Solar reverse osmosis seawater desalination system comprises solar photovoltaic power generation reverse osmosis desalination and solar thermal energy-driven reverse osmosis seawater desalination [14–17]. The major advantages of solar seawater desalination are the following: First, CO_2 emission of the solar energy used in photo thermal seawater desalination is low, and the CO_2 emission of photovoltaic power generation is 43∼73 g of/kWh [4]; Second, with many characteristics like technologically mature, system operating independent, free from the restrictions of the power and steam, random combining, strong adaptability and so on, solar seawater desalination shows great superiority in islands and desert areas which are lacking in electricity and steam. The main disadvantages are: Firstly, it is restricted by natural conditions to some extent. Secondly, the solar fluctuation may lead to unstable fresh water production, which will result in having difficulties in guaranteeing a large scale of stable and reliable water supply for cities. Thirdly, it needs high initial investment. The unilateral cost of solar power seawater desalination is higher than coal-fired, nuclear energy and wind energy desalination projects, so the economic efficiency is low. Lastly, it will be limited by factors like the conversion efficiency of solar thermal and photovoltaic. Besides, covering large scale of areas, which means solar seawater desalination, is only fit for islands and marine mobile platforms that are out of electricity and steam and demand small amounts of freshwater [18–20].

2.4. Nuclear energy

Nuclear technology consists of nuclear energy seawater desalination, desalination technology and their connecting technology. Since the nuclear reactor can supply heat and generate electricity, the nuclear reactor can be coupled with any other conventional desalination processes in principle. Selection of nuclear energy seawater desalination requires considering the region's demands for electricity and water, the economic result, safety, reliability, and a flexible operation of the nuclear energy desalination, assuring that the product water not being polluted, a constant supply of electricity and fresh water, and having no harmful impacts on surrounding residents and the environment [21]. The main advantages of nuclear energy seawater desalination are as follows: First, CO_2 emission of the nuclear energy is at 0.74∼24 g of/kWh [4], which is quite low. Second, be able to provide high-quality and reliable electricity, and supply the urban of large-scale stable and reliable water at the same time. Third, it is a scale economy. The main disadvantages are as follows: First, nuclear energy seawater desalination engineering technology is relatively complex, and the technology has not been fully mature. Secondly, the construction, management and operation of a nuclear energy seawater desalination project is a pretty complicated process, which is influenced by lots of factors, including reliability of the system, investment costs, optimizing the design of the interfaces of the nuclear reactors and the desalination system.

2.5. Other energy sources

Ocean energy includes wave energy and tidal energy. The gravity of the moon, the sun, and other celestial bodies leads to tidal changes of sea levels and that kind of changes make the energy exist. As two kinds of clean, renewable energy in the ocean, featuring tremendous development potential. According to related experiments and mathematical simulations, compared with the seawater desalination system that uses fossil fuels as the energy source, wave-powered seawater desalination is economic on conditions that

Table 1
Analyses and comparisons of various energy seawater desalinations

Features Energy resources	Advantages	Disadvantages
Fossil energy	Technologically mature; stable; having great economic competitiveness	Not low-carbon; great damage to the environment; restricted by energy security
Wind energy	Operated independence; random combinations; adaptable; low-carbon	Water production is not stable enough; small-scale water production; the economic efficiency is not so high
Solar energy	Out of limitation of electricity and steam; random combinations; adaptability; low-carbon	Limited by natural conditions; the water production is unstable; the water production is small-scale; initial investment of photovoltaic power generation desalination is huge; economic competitiveness is weak
Nuclear energy	Low-carbon and environmentally friendly; providing stable produced water; large-scale production of water; economic	Complex process; immature technology; complicated management; high security requirements; high cost of investment; hard to unify the public awareness
Other energy resources (ocean energy, LNG, geothermal energy, biomass energy)	Huge development potential; economy of scale; certain economic efficiency; low-carbon	Immature technology and the majority are still in research

the scale of the wave-powered seawater desalination reaches Nissan 1,000 tons of water. These two energy desalination technologies are still very attractive in coastal areas or island areas that possess rich wave energy and tidal energy but lack of freshwater resources, In addition, the seawater desalination technology utilizing cold energy produced from liquified natural as gasification processes, and the one utilizing geothermal energy and biomass energy are also in research [22]. To conclude, We obtain the analyses and comparisons of various seawater desalination as showed in Table 1.

3. Comprehensive evaluation system

Comprehensive evaluation system refers to the method, which use multiple indicators to evaluate multiple evaluation factors. The basic idea is that multiple indicators transform into one to reflect the consolidation of indicators. By integrating expert investigation method, AHP and fuzzy evaluation theory, we establish the comprehensive evaluation system that combines energy technologies and seawater desalination, evaluate each project's comprehensive benefit so as to embody the overall competitiveness of each project.

3.1. Evaluation indicators system

Technical Economic Evaluation of the applications of various energy technologies in seawater desalination is a complex Systems Engineering, which involves all kinds of factors, so establishing an evaluation indicators system is the basic work of a Technical Economic Evaluation. And it remains a nut to be solved about establishing the evaluation indicators system. For this reason, it will be feasible to solve the problem through analysis and judgment that follow certain principles. This Comprehensive Evaluation System is an organic whole that focuses on five basic principles: scientific principle, feasibility principle, hierarchy principle, focus and comprehensiveness indicators, and relative independence. According to the commonly used evaluation indicators, factors for the consideration of domestic similar projects, and the advice of some experts included, determining the technical and economics evaluation of the seawater desalination projects [23–25]. Under the comparison of several kinds of energy seawater desalination projects, we build the comprehensive evaluation system as showed in Table 2.

3.1.1. Technical factors

Technical factors mainly include energy technologies, seawater desalination technologies, and the coupling technologies adopted. As a result, a unidirectional and systemic consideration is needed. In order to meet the process requirement, it raises higher demands for energy technologies and seawater desalination technologies by investigating the complexity, the reliability, and the advancement of the technique and technology and judging the inferiors and superiors of the project from levels among all the alternative proposals.

Table 2
The comprehensive evaluation system of various energy technologies applied in seawater desalination

1st indicators variable	1st level indicators name	2nd level indicators variable	2nd level indicators name
u_1	Technical factors	u_{11}	Technological complexity
		u_{12}	Technological reliability
		u_{13}	Technological advancement
u_2	Environmental factors	u_{21}	Environmental impact
		u_{22}	Environmental requirement
u_3	Social factors	u_{31}	Social benefit
		u_{32}	Social cost
u_4	Economic factors	u_{41}	Investment cost
		u_{42}	Investment income
		u_{43}	Operation cost
u_5	Management factors	u_{51}	Management science
		u_{52}	Management complexity
		u_{53}	Management level

3.1.2. Environmental factors

In this paper, the environmental factors are mainly considered from two aspects, which are the environmental requirements and the environmental impacts. The environmental requirements include the environmental conditions for energy technologies and seawater desalination technologies, such as geographical position, seawater quality, and weather situation. At the same time, the environmental impacts include the influences on surroundings of the energy technologies and seawater desalination technologies, such as the carbon emission of different energy technologies and the pollution status of water and the influences on surroundings of various seawater desalination technologies, and all of that will be concluded in the evaluation system as environmental factors.

3.1.3. Social factors

Social factors analyze the benefit and the cost the project will brings to the society. Focusing on the social benefit, it contains resolving regional contradictions of lacking fresh water and energy, and welfare it brings to the society. Considering the social cost, it includes the adverse effects the project may bring to the air quality, seawater quality and public security: furthermore, adverse effects may also be brought to local industries and residents' life. So it is essential to investigate the benefit and burden the project may bring to the society and to get public approval and support.

3.1.4. Economic factors

Economic factors mainly include the investment cost, investment income and operation cost of the project. There are two parts composing the investment cost which are the cost it takes when energy technologies are applied in seawater desalination process, and the investment cost for the seawater desalination. And the investment income includes the income from the water production of seawater desalination and the under-expenditure of energy after meeting the need of seawater desalination. In addition, operation cost consists of the cost it takes when supplying power and heat and the running cost of seawater desalination. Economic factors investigate the feasibility of the project from the perspective of financial and estimate the income of investment.

3.1.5. Management factors

Management factors are mainly about three aspects, management difficulties, scientific nature of management and management levels. The coupling of energy resources and seawater desalination is not merely coupling technologically; it is more about the coupling of management. Management difficulties mainly evaluate the difficulties to management, which are produced from the integration of energy technologies and seawater desalination. Scientific nature of management mainly judges whether the various resources are disposed scientifically according to project management and accorded with internal regularity of the project. Management levels mainly access the organizing ability, professional ability and coordination ability of the managers in project implementation.

3.2. Division of evaluation level

Due to existing too many indicators, we can ascertain the evaluation set is: $V = \{v_1, v_2, v_3, v_4\}$ = (pretty satisfactory, satisfactory, general, bad). Among them, pretty satisfactory means expert feels very satisfied with the indicator, as for positive indicators, the expert holds that the indicators are high; and as for negative indicators, the expert holds that the indicators are low. Satisfactory shows that expert are satisfied with the indicator but not very satisfied, namely it is slightly inferior to pretty satisfactory. To positive indicators, the expert regards that the indicator is high but not so high, and to negative indicators, the expert holds that the indicator is low but not so low. Bad means expert feels very dissatisfied with the indicator, and the expert thinks it is the worst to make a person feel satisfied. As for positive indicators, the expert holds that the indicators are lowest; and as for negative indicators, the expert holds that the indicators are highest. General means the expert evaluates the indicator value as slightly better than bad but worse than a satisfactory or cannot achieve a satisfactory. To positive indicators, the expert regards that the indicator value is a little higher than the lowest and is not high, and to negative indicators, the expert holds that the indicator cannot reach the highest but it is not so low [26–28].

3.3. Applying AHP to weights distribution

AHP is the method that decision-making elements are decomposed into several levels, and qualitative and quantitative analysis is used on this basis. It is characterized on the basis of in-depth analysis of the complex decision-making nature of the problem, the influencing factors and internal relations, using less quantitative information to make the decision-making process of thinking mathematical. AHP provide a simple method of decision-making for Multi-objective, multi-criteria or structural properties of the complex decision-making problem.

In this paper, the authors hold that AHP provides scientific and feasible ideas for target risk evaluation the AHP utilizes expert experience and knowledge to set up the indicators system, tests and evaluates the consistency of expert opinions through consistency test, which effectively combines qualitative analysis with quantitative analysis [29–30]. AHP not only makes up for the deficiencies of expert investigation method, but also gives the quantitative relations of risk factors comparisons from the mathematical perspective. Among the evaluation factors considered in this paper, the first- level factors are {technological factors, environmental factors, social factors, economic factors, management factors}, denoted by $U = \{u_1, u_2, u_3, u_4, u_5\}$, weighted $W = (w_1, w_2, w_3, w_4, w_5)$. Applying AHP to define the weight of each indicator, the point is to accurately determine the relative importance of indicators at all levels from top to the bottom.

3.3.1. Constructing judgement matrix

This step is to compare the impacts on project risk of indicators at each level, so as to determine their weights in project. According to evaluation indicator system on seawater desalination project, the first-grade indicators are from u_1, to u_5, and it is not easy to determine their influence degree to project, directly, but that can be determined by ordering with paired comparison of fuzzy mathematics. Compare two first grade indicators u_i to u_j each time, the influence ratio of u_i and u_j to the project is denoted by u_{ij}, Table 2 shows its value range, that is, judgment matrix $A = (u_{ij})$ 5×5 represents all comparison results, and its implications are showed in Table 3.

3.3.2. Calculating weights of indicators in each level

According to the information supplied by judgment matrix, power method can be used to get the largest eigenvalue and the eigenvector of arbitrary accuracy. However, the judgment matrix itself exists certain errors, while the weights of each project or each indicator obtained by AHP can be described as some kind of qualitative concepts, thus good accuracy is not necessary. Therefore, this paper utilizes a simpler approximate computation–root method, to calculate the relative weight at each level of the projects or the indicators, the steps are as follows [24–30]:

Table 3
Meaning of each scale of the judgment matrix

Importance degree	Implications
1	u_i and u_j equally important
3	u_i is a bit more important than u_j
5	u_i is obviously more important than u_j
7	u_i is strongly more important than u_j
9	u_i is extremely more important than u_j

Note: 2, 4, 6, 8 are the medians of the adjacent judgments, 1/2, 1/3, 1/4, 1/5 … are the obverse of the judgments.

(1) Calculating the factor's product of each line of the judgment matrix $M_i = \prod_{j=1}^{n} u_{ij}, i = 1, 2, \ldots n$.
(2) Calculating the nth root of m $W_i = \sqrt{[n]M_i}$.
(3) Make normalization processing of the vector $W = (w_1, w_2, w_3, w_4, w_5)^T$ to get eigenvectors.
(4) Consistency test. When conducting pairwise comparison for the indicators affecting appraisal objects, judgment cannot be in full accord and there must be estimation errors, so judgment matrix may not be consistent matrix. For the sake of reliability, consistency test must be taken after normalized eigenvector are calculated. Its method is to calculate random consistency indicator

$$CI = \frac{\lambda_{\max} - n}{n - 1}$$

$$\lambda_{\max} = \frac{1}{n}\sum_{i=1}^{n} \frac{\sum_{j=1}^{n} u_{ij} W_j}{W_i}$$

where $\lambda_{\max}$ is the largest eigenvalue of judgment matrix, n is the order of the judgment matrix. Finally, calculate consistency ratio

$$CR = \frac{CI}{RI}$$

where RI is mean random consistency indicator, which can be find from Table 4. When $CR<0.1$, the consistency of judgment matrix can be accepted; when $CR \geqslant 0.1$, the judgment matrix should be modified approximately, until $CR<0.1$ is satisfied.

According to the formulas mentioned above, we obtain the largest eigenvalue of A, which is $\lambda_{\max} = 5.0754$ and then test it with consistency test: CI = (5.0754–5)/(5–1)=0.0189, CR = CI/RI = 0.0189/1.12 = 0.0168 < 0.1, and the consistency has been tested (found from Table 4). Normalizing the eigenvectors and then we get the weight coefficient of the first grade indicator: $W = (0.2503, 0.1864, 0.1864, 0.2232, 0.1597)^T$. Similarly, the weight coefficients of the second grade indicators are:

Table 4
Mean random consistency indicator

Order	RI	Order	RI	Order	RI
1	0	6	1.26	11	1.52
2	0	7	1.36	12	1.54
3	0.52	8	1.41	13	1.56
4	0.89	9	1.46	14	1.58
5	1.12	10	1.49	15	1.59

$w_1 = (0.3333,\ 0.3333,\ 0.3333)^T$; $w_2 = (0.7,\ 0.3)^T$; $w_3 = (0.5,\ 0.5)^T$; $w_4 = (0.30, 0.54, 0.16)^T$; $w_5 = (0.4, 0.4, 0.2)^T$.

3.3.3. Determination of single-factor

Starting judgment from a single indicator to determine the membership degree of the judgment target to the judgment set V is called the single-factor fuzzy evaluation. Take technological factor U_1 for analysis, in order to build up assessment matrix B_1. Suppose the judgment target is judged form the factor set U_1's ith factor U_{1i}, and U_{1i}'s membership degree of the judgment set's jth factor is r_{ij}, then the judgment results can be represented by a fuzzy set $R_{1i} = (r_{i1}, r_{i2}, r_{i3}, r_{i4})$. R_{1i} is called the single- factor fuzzy evaluation set of technological factor u_1, and the matrix $R_1 = (r_{11}, r_{12} \ldots r_{14})^T$ made up of it is known as the single factor evaluation matrix. Matrix R_1 can be seen as a fuzzy transform relation between the factor set u_1 and judgment set V. If n experts are invited to vote on all the indicators of (u_{11}, u_{12}, u_{13}) in accordance with the evaluation set $V = \{v_1, v_2, v_3, v_4\}$, and there are m_{ij} experts who vote on j-level to the technological factor's jth indicator, and then the probability that the total jury chose j-level for this indicator can be considered as $b_{ij} = m_{ij}/n$. According to the probability statistics of the jury's choices of levels on the indicators, a row matrix of the evaluation of u_1's ith indicator can be obtained: $R_{1i} = (r_{i1}, r_{i2}, r_{i3}, r_{i4}) = (m_{i1}/n, m_{i2}/n, m_{i3}/n, m_{i4}/n)$.

3.3.4. Fuzzy comprehensive evaluation model

Fuzzy comprehensive evaluation, namely converting a fuzzy set A from the universes of the evaluation factor set U into a fuzzy set B from the universes of the assessment set V through a fuzzy relation R. That is:

$$B = W \circ R = (w_1, w_2, \ldots, w_n) \circ \begin{bmatrix} r_{11} & r_{12,} & ,\ldots, & r_{1n} \\ r_{21} & r_{22} & ,\ldots, & r_{2n} \\ & & ,\ldots, & \\ r_{n1} & r_{n2} & ,\ldots, & r_{mn} \end{bmatrix} = (b_1, b_2 \ldots bn). \quad (1)$$

The formula above is the mathematical model of fuzzy comprehensive evaluation. In this formula, B presents the result of fuzzy comprehensive evaluation, it is a m-dimensional fuzzy row vector; W is the weight set of fuzzy comprehensive evaluation factors, it's a n-dimensional fuzzy row vector; R is a fuzzy relation from U to V and it's a $(n \times m)$matrix. The element r_{ij} ($i = 1, 2, \ldots, n$; $j = 1, 2, \ldots, m$) means starting from the ith element, making the possibility of the jth assessment, namely the membership degree. b_j represents the membership degree of comprehensive evaluation value that belongs to jth level. If $b_k = \max[b_1, b_2, \ldots b_n]$, we consider the project's comprehensive evaluation level as the kth level.

4. Example analysis

Taking the seawater desalination of an island for example, evaluate the coupling technology of seawater desalination and various energy technologies and select the optimal energy technology for the seawater desalination workshop of the island. Located in the southeastern coast of China, this island possesses rich seawater resources but lacks fresh water and is going to build a 50,000∼100000 m^3/d seawater desalination workshop. Seawater turbidity of this area is high and seawater has been polluted to some degree. The alternative energy resources include fossil energy (coal and petroleum), wind energy, solar energy, nuclear energy and so on, the alternative seawater desalination technologies include MSF LT-MED MVC and other distillation methods, PO ED and other membrane methods. So independent power generation is separately compared with grid-connected power generation to evaluate the energy schemes, and the combination schemes are showed in Table 5.

According to formulas mentioned in III. 3), calculate the weights of 13 indicators and the weights are: $W = (0.0834, 0.0834, 0.0834, 0.1305, 0.0559, 0.0932, 0.0932, 0.0670, 0.1205, 0.0357, 0.0639, 0.0639, 0.0319)$. Get the fuzzy relation R by inviting 10 experts, utilizing their professional knowledge about seawater desalination and energy technologies, evaluating the 13 factors in the alternative scheme showed in Table 5, and calculating the membership degree of each indicator of each scheme. Finally, we obtain satisfaction evaluation degree of 26 combination schemes according to formula $B = W \circ R = (b_1, b_2, \ldots, bn)$ and results are showed in Table 6.

In scheme 1, e.g. we analyses the evaluation result of each scheme in Table 6. First, based on expert scoring, we draw the scheme's membership vector matrix $R_{13\times4}$:

$$R_{13\times4} = \begin{bmatrix} 0.1 & 0.2 & 0.6 & 0.1 \\ 0.2 & 0.2 & 0.4 & 0.2 \\ 0.2 & 0.4 & 0.3 & 0.1 \\ 0.4 & 0.3 & 0.1 & 0.2 \\ 0.3 & 0.3 & 0.3 & 0.1 \\ 0.2 & 0.3 & 0.3 & 0.2 \\ 0.3 & 0.4 & 0.2 & 0.1 \\ 0.1 & 0.1 & 0.7 & 0.1 \\ 0.2 & 0.2 & 0.5 & 0.1 \\ 0.2 & 0.3 & 0.4 & 0.1 \\ 0.2 & 0.2 & 0.3 & 0.3 \\ 0.1 & 0.2 & 0.6 & 0.1 \\ 0.2 & 0.2 & 0.5 & 0.1 \end{bmatrix} \quad (2)$$

Then, according to Eq. (1), we calculate results of the comprehensive evaluation of the scheme 1,

$$S = W \times R_{13\times4} = (b_1, b_2 \ldots bn) = (0.29, 0.31, 0.35, 0.05) \quad (3)$$

In (3), b_j represents the degree of membership of the to the jth level. According to evaluation set: $V = \{v_1,\ v_2,\ v_3,\ v_4\}$ = (pretty satisfactory, satisfactory, general, bad), the scheme's membership belonging to pretty satisfactory level, satisfactory level, general level and bad level are followed by 0.29, 0.31, 0.35, and 0.05. When $b_k = \max(b_1, b_2 \ldots b_n)$, the scheme's evaluation degree is level k. Among the scheme's four memberships, the third is 0.35 which is maximum one. So the scheme's corresponding evaluation degree is "general". In the same way, we can calculate other schemes' evaluation degree that show in the rightmost column of Table 6.

The results of further analysis from Table 6 are showed in Table 7. Scanning Table 7, we can find that among 26 alternative combination schemes, there is one result "pretty satisfactory" which is scheme 21 (wind electricity (grid-connected)–RO). There are 7

Table 5
Combination scheme of various energy and seawater desalination

Energy resources	Seawater desalination technologies	
	Distillation methods	Membrane methods
Fossil energy	Fossil energy heating–MSF LT-MED MVC	Fossil energy generation (independent or grid-connected)–RO ED
Wind energy	Wind power–MVC	Wind electricity (independent or grid-connected)–RO ED
Solar energy	Solar thermal–MSF LT-MED MVC	PV (independent or grid-connected)–RO ED
Nuclear energy	Nuclear heating–MSF LT-MED MVC	Nuclear electricity (independent or grid-connected)–RO ED

Table 6
Evaluation degree of combination scheme of various energy and seawater desalination

Scheme number	Combination schemes	Category	The evaluation results	Evaluation degree
1	Fossil energy heating–MSF	Distillation method	(0.29, 0.31, 0.35, 0.05)	General
2	Fossil energy heating–LT-MED	Distillation method	(0.27, 0.39, 0.15, 0.19)	Satisfactory
3	Fossil energy heating–MVC	Distillation method	(0.18, 0.19, 0.39, 0.24)	General
4	Wind power–MVC	Distillation method	(0.15, 0.19, 0.44, 0.22)	General
5	Solar thermal–MSF	Distillation method	(0.10, 0.26, 0.40, 0.24)	General
6	Solar thermal–LT-MED	Distillation method	(0.09, 0.23, 0.37, 0.31)	General
7	Solar thermal–MVC	Distillation method	(0.10, 0.16, 0.33, 0.41)	General
8	Nuclear heating–MSF	Distillation method	(0.19, 0.28, 0.37, 0.16)	General
9	Nuclear heating–LT-MED	Distillation method	(0.23, 0.35, 0.21, 0.21)	Satisfactory
10	Nuclear heating–MVC	Distillation method	(0.15, 0.25, 0.36, 0.24)	General
11	Fossil energy generation (independent)–RO	Membrane method	(0.21, 0.30, 0.27, 0.22)	Satisfactory
12	Fossil energy generation (independent)–ED	Membrane method	(0.23, 0.25, 0.31, 0.21)	General
13	Wind electricity (independent)–RO	Membrane method	(0.11, 0.13, 0.45, 0.31)	General
14	Wind electricity (independent)–ED	Membrane method	(0.09, 0.12, 0.38, 0.41)	Bad
15	PV (independent)–RO	Membrane method	(0.11, 0.13, 0.35, 0.41)	Bad
16	PV (independent)–ED	Membrane method	(0.08, 0.16, 0.37, 0.39)	Bad
17	Nuclear electricity (independent)–RO	Membrane method	(0.24, 0.36, 0.28, 0.12)	Satisfactory
18	Nuclear electricity (independent)–ED	Membrane method	(0.23, 0.29, 0.34, 0.14)	General
19	Fossil energy generation (grid-connected)–RO	Membrane method	(0.19, 0.25, 0.37, 0.19)	General
20	Fossil energy generation (grid-connected)–ED	Membrane method	(0.21, 0.19, 0.36, 0.24)	General
21	Wind electricity (grid-connected)–RO	Membrane method	(0.38, 0.31, 0.16, 0.15)	Pretty satisfactory
22	Wind electricity (grid-connected)–ED	Membrane method	(0.30, 0.33, 0.25, 0.12)	Satisfactory
23	PV (grid-connected)–RO	Membrane method	(0.25, 0.28, 0.23, 0.24)	Satisfactory
24	PV (grid-connected)–ED	Membrane method	(0.13, 0.17, 0.38, 0.32)	General
25	Nuclear electricity (grid-connected)–RO	Membrane method	(0.21, 0.36,0.25, 0.18)	Satisfactory
26	Nuclear electricity (grid-connected)–ED	Membrane method	(0.18, 0.26, 0.39, 0.27)	General

Table 7
Comparison of evaluation result of different types of desalination combination schemes

Combination schemes	Evaluation degree	Pretty satisfactory		Satisfactory		General		Bad	
	Total account	Account	Percentage	Account	Percentage	Account	Percentage	Account	Percentage
All schemes	26	1	4	7	27	15	58	3	12
Distillation schemes (1–10)	10	0	0	2	20	8	80	0	0
Membrane schemes (11–26)	16	1	6	6	38	6	38	3	19
Fossil energy schemes (1–3, 11, 12, 19, 20)	7	0	0	2	29	5	71	0	0
Wind energy schemes (4, 13, 14, 21, 22)	5	1	20	1	20	2	40	1	20
Solar energy schemes (5–7, 15, 16, 23, 24)	7	0	0	1	14	4	57	2	29
Nuclear energy schemes (8–10, 17, 18, 25, 26)	7	0	0	3	43	5	71	0	0
Independent power generation schemes (11–18)	8	0	0	2	25	3	38	3	38
Grid-connected power generation schemes (19–26)	8	1	13	3	38	4	50	0	0

schemes that are evaluated as "satisfactory", 15 schemes are evaluated as "general" and 3 schemes are evaluated as "bad" .20% of the evaluation results are "satisfactory" or "pretty satisfactory" by means of distillation method (schemes 1–10) while 44% of the evaluation results are "satisfactory" (6%) or "pretty satisfactory" (38%) by means of membrane method (scheme 11–26), so we can say that membrane method is better than distillation method on the whole; By comparing four energy technologies we find that 29% of evaluation results of fossil energy scheme are "satisfactory" (29%) or "pretty satisfactory" (0%), the percentage of that of wind energy is 40% among which there are "satisfactory" (20%) or "pretty satisfactory" (20%), while the percentage of that of solar energy is 14% and nuclear energy is 43%; 25% of independent power generation seawater desalination are evaluated as "satisfactory" (0%) or "pretty satisfactory" (25%) and the percentage of that of grid-connected power generation is 38%. Integrating these evaluation results we can conclude that seawater desalination using membrane method is superior to distillation method; among these four energy technologies, nuclear energy and wind energy is better, fossil energy takes the second place and solar energy is the poorest; the selection of grid-connected power generation is generally better than independent power generation. Then, according to the evaluation result of the level of satisfaction membership, we choose three schemes that are wind energy (grid connected) reverse osmosis seawater desalination (scheme 21), nuclear energy (grid connected) reverse osmosis seawater desalination (scheme 25) and fossil energy low temperature multiple effect seawater desalination (scheme 2).

5. Conclusions

At present, in addition to fossil energy and other conventional energy, the application of clean energy resources like wind energy, solar energy, and nuclear energy in seawater desalination is rising around the word. It represents the future direction of desalination technology development, meeting the need of a resource-saving and eco-friendly society. And the technology has a great prospect of applying in regions in serious shortage of fresh water and energy. This paper concludes the advantages and disadvantages of various schemes by analyzing and comparing seawater desalination technologies of various energy and utilizes fuzzy comprehensive evaluation method and analyzes a typical example. The method in this paper provides a scientific evaluation method for the application of energy technologies in seawater desalination. However, this methodology also has limitations to some degree, for example, the weights of indicators is mainly by means of expert scoring, so the objectivity of it needs more discussions even though it has pass the consistency check. Besides, it needs more data to verify whether the indicator has covered all the factors that affect the scheme.

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