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The Ranking of Southern Ports and Islands of Iran for Seawater Desalination Plants Using ELECTRE III Method

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A B S T R A C T

The energy insecurity, environmental pollution, climate change and a reduction of rainfall in some countries are the prime examples of consequences of the excessive dependence on the fossil fuels in the world. This study suggests that in some of southern islands and coastal areas of Iran, two main problems, the growing shortage of potable water and air pollution, can be solved by building a wind-powered seawater desalination plant in the area. To evaluate such project, the sites that may provide the highest efficiency should be identified. In this study, 10 ports and 5 islands, which suffer from water shortage but have access to seawater, are identified as preliminary candidate sites for such project in south of Iran. The criteria influencing the suitability of a location are wind power density, economic feasibility, topographic condition, frequency of natural disasters, population and distance between the wind farm and the desalination facility. After calculating the value of each criteria, the locations are ranked using the ELECTRE III method and the results are validated using the PROMETHEE method. In conclusion, the results of ranking techniques show that Qeshm Island is the best location for construction of a wind-powered seawater desalination plant.

1. INTRODUCTION

A rapid growth of the population of world and consequently a demand for the basic resources, such as food and water, and other essentials, such as adequate housing and transportation have observed in the last century. The growing importance and global interest in energy resources, security and consumption are other results of this rapid growth [1]. This interest is augmented by the global awareness about the rate of extraction and consumption of fossil fuel energy sources and their declining reserves. Therefore, the continued researches on solutions involving alternative resources have become an essential part of the global effort to avoid the future energy shortages and achieve sustainable development in this regard.

In recent decades, the environmental pollution due to fossil resources, its worldwide manifestation in ozone depletion and global warming has received increasing attention from public and academic communities [2]. The less known and rather local consequence of pollution is the exacerbation of respiratory and cardiovascular diseases threatening the inhabitants of large cities and particularly industrial areas, as one of the main sources of greenhouse gas emission and consequent problems due to the concentration of many varieties of industrial activities relying on fossil fuels as an essential part of the production process or main source of energy. Today, fossil fuels are far from the exclusive sources of energy and are gradually being replaced by other fuels which are free, without pollution and unlimited. These alternatives include wind, solar, and biomass power which are collectively known as renewable and sustainable energies. Among these, wind energy is the most convenient source widely available around the globe [3]. This energy is being utilized in the many countries across five continents and is the cornerstone of many ongoing research and development efforts. In essence, wind energy is the wind force converted into electricity by a wind turbine and there are two major varieties, horizontal axis and vertical axis. Another serious issue, that has recently challenged multiple developing countries, is the persistent water scarcity due to the combined effect of climate change and inefficient and excessive use of strained water resources, which threatens the future of not only humans but all living beings inhabiting these countries. Iran is one of the countries at the serious risk of severe water shortage caused by reduced precipitation, years of excessive and irresponsible utilization of water

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resources [4]. By exacerbating condition of water resources and particularly underground sources in the recent years, the authorities in charge of water resources of Iran have declared a state of water consumption emergency [5]. However, the local research literature on possible solutions other than water conservation has been scarce. One of these possible solutions is water purification and desalination in coastal areas and particularly islands. Considering the current state of water supplies and consumption in Iran and in line with the objective of sustainable development based on the renewable energy supplies, this study aims to locate the suitable sites for implementation of a wind-powered seawater purification and desalination projects in the southern coastal areas and islands of Iran, which are suffering from an increasingly severe water scarcity problem. For this purpose, after a preliminary research, 5 islands and 10 ports are identified as the best candidates for such project, and then criteria involved with performance of such facility in these sites are determined. Finally, the best location is identified using the multi-criteria decision making method ELECTRE III, and validity of its results is checked by the PROMETHEE method.

1.1. Water situation in Iran

Iran has an area of 1,648,195 square kilometers (18^{th} largest in the world) and a population of over 80 million (according to the latest census, 2016) [6, 7]. The size and geographical location of Iran cause a diverse climate: Caspian temperate in the north, Mediterranean in the northwest, dry cold mountainous in the west, semi-arid in the east and center, and dry and coastal in the south [6]. It should be mentioned that more than half of Iran's land area has an arid or semi-arid climate, and these areas has historically struggled with mild water scarcity problem [5]. But recently, this problem has become more severe in the central and southern provinces such as Yazd, Kerman, Khuzestan, Hormozgan and Sistan-Baluchestan [4].

The north, northwest and northeastern parts of the country have better precipitations brought by the Mediterranean and Siberian air systems, and are thus spared from the water crisis hurting their southern neighbors, which have experienced ever deteriorating water conditions in the past few years. While generally arid, the southern coast of Iran is located along the Persian Gulf and Oman Sea with the unlimited supply of seawater, which can be utilized for addressing the water scarcity problem in a local scale by the limited production of potable water using water purification and desalination solutions. If successful, such projects can even be expanded to serve more inland regions.

1.2. Wind energy in Iran

Like many other countries around the globe, Iran has great wind and solar energy potentials [8], which if researched and utilized properly, can serve as the foundation of sustainable development and ultimately oil/gas independent energy security. The second largest wind generation center of Iran is Binalud with 43 turbines yielding about 28.5 MW energy generation capacities [9, 10]. Fig. 1 illustrates the installed wind capacity in Iran over the last 10 years.

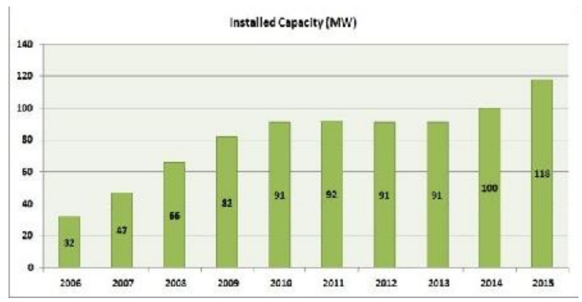

Figure 1. The installed wind capacity in Iran from 2006 until the end of 2015 [10]

According to the renewable nature of the wind, it can play a significant role in long-term energy and development plans of any country. This however requires some preparations, such as feasibility analyses and technical-economic evaluations so that efforts would cause the optimal realization of available wind energy potentials.

While being renewable, wind is not a reserved or storable energy, so any day passing without realization of an existing wind potential is equivalent to a certain amount of energy that is lost forever, thus any such potential is best to be identified and harvested as quickly as possible. The aim of this study is to identify the best locations in the southern coastal areas and islands of Iran, for building a wind-powered seawater desalination plant.

1.3. Seawater desalination

The primary goal of seawater desalination process is producing potable water. For this purpose, seawater must be purified and desalinated, then distributed for domestic use in residential areas. This process needs a multitude of systems and equipment that all require electricity to work.

One of the major components of desalination plant is pretreatment device, where seawater is subjected to preliminary treatment processes such as filtration, softening and adsorption before being let into primary desalination machine. Another major component of desalination plant is a high-pressure pump providing the necessary pressure for pumping of water from the sea. This component is also powered by electricity [11, 12]. In summary, the required energy for desalination of seawater ranges from 3.9 to 5.6 kWh/m^3 depending on factors such as recovery energy, design of pretreatment device, mechanism of desalination, and type of membrane [13, 14].

2. GEOGRAPHICAL PROFILE

Southern coastline of Iran has a dry and semi-arid climate and is suffering from severe water scarcity problem. On the other hand, vicinity to the Persian Gulf and Oman Sea can be leveraged to alleviate the issue. As mentioned, the aim of this study is ranking the islands and ports located in southern region of Iran in terms of their suitability as the site of a wind-powered seawater desalination plant. Location of the studied regions is shown in Fig. 2, and their latitudes and longitudes are given in Table 1.

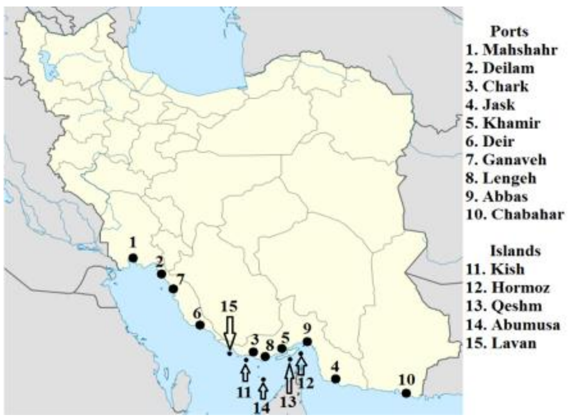

Figure 2. Location of the studied regions

TABLE 1. Geographical coordinates of the studied regions [15]

Location	longitude	Latitude
Mahshahr Port	49°11'E	30°33'N
Deilam Port	50°10'E	30°03'N
Chark Port	54°16'E	26°43'N
Jask Port	57°46'E	25°38'N
Khamir Port	55°34'E	26°56'N
Deir Port	51°56'E	27°50'N
Ganaveh Port	50°31'E	29°34'N
Lengeh Port	54°53'E	26°33'N
Bandar Abbas	56°17'E	27°11'N
Chabahar Port	60°38'E	25°17'N
Kish Island	53°58'E	26°32'N
Hormoz Island	56°27'E	27°10'N
Qeshm Island	56°05'E	26°55'N
Abumusa Island	55°01'E	25°52'N
Lavan Island	48°13'E	30°20'N

3. RESEARCH METHODOLOGY

In this study, we first evaluate the criteria involved by performance the wind-powered seawater desalination plant in a given region, which include wind power density, cost, topographic conditions, frequency of natural disasters, population, and distance of the wind farm from the plant. The results are then used to identify the best location for the construction of such the plant. Achieving this goal requires a preliminary investigation for choosing the best location in order to avoid the later financial losses. The decision support models developed to facilitate sound decisions making are divided into two groups: multi-objective models and multi-criteria models. Multi-objective models (such as goal programming and panel data analysis) are often used for decisions that involve simultaneous optimization of several conflicting objectives [16]. Multi-criteria models however are often used to evaluate, prioritize and choose among several alternatives according to multiple criteria. These methods often involve assigning a weight to each criterion based on its importance for the objective [17]. In this study, locations are prioritized using the multi-criteria decision making method ELECTRE III, with the criteria concerning the suitability of the site weighted by the Entropy method. Finally, the results are validated by the PROMETHEE method.

3.1. ELECTRE III method

ELECTRE is a decision analysis method introduced by Bernard Roy to address the shortcomings of other multi-criteria decision-making methods [18]. Today, ELECTRE refers to a family of techniques including ELECTRE I, II, IS, III, IV, TRI developed for multi-criteria decision-making problems of the different nature.

The advantage of this method is its ability to use quantitative and qualitative criteria as a measure to rank the alternatives or options by pairwise comparisons. In this method, problems are expressed as a set of criteria and alternatives and are solved based on the preference [19]. Traditional methods of this group consider two relations between the alternatives: indifference and preference. ELECTRE III has become known as one of the most powerful multi-criteria decision-making methods for efficient ranking [20], partly because of incorporating additional concepts including preferences, indifference, and veto thresholds [21], and also because of its non-compensatory nature which prohibits a good score in one criterion to compensate for a terrible score in another criterion [22]. This technique consists of following steps:

Step 1: Constructing the decision matrix: In the first step, we construct a matrix of size m×n (where n is the number of alternatives and m is the number of criteria) representing the values of criteria for different alternatives. In this matrix, the element concerning alternative a_i and criterion k is represented by g_{kai} [23].

Step 2: Defining the thresholds and weighting the criteria: In this ranking technique, the base approach of the method to identification of superior alternatives is improved by three thresholds: indifference threshold (q), preference threshold (p) and veto threshold (v). Decision makers have to set these thresholds separately for each criterion according to the rule $v_i>p_i>q_i>0$ [33]. For example, threshold of alternatives of a_1 and a_2 and criterion j are defined as Equations (1), (2) and (3) [24, 25]:

$$|g_{ja_1} - g_{ja_2}| \leq q_j \quad (1)$$

$$g_{ja_1} - g_{ja_2} > p_j \quad (2)$$

$$g_{ja_2} - g_{ja_1} > v_j \quad (3)$$

Eq. (1) shows that in comparison to criterion j, alternative a_1 is indifferent to alternative a_2, and alternative a_2 is indifferent to alternative a_1; Eq. (2) expresses that in terms of criterion j, alternative a_1 is preferred to alternative a_2; and Eq. (3) expresses that the preference relation will be disregarded if for criterion j, alternative a_1 is not as superior over a_2 as stated in the equation. In this method, the thresholds need to be set before any ranking. Weights or relative importance of criteria are typically defined by experts and decision-makers, and their total sum must be equal to 1. In this study however the criteria are weighted using the entropy method.

Step 3: Constructing the partial concordance matrix for every criterion: In this step, the formed decision matrix in the first step is used alongside the thresholds set in the second step to construct the concordance matrix (c_k) for each criterion according to the relation between alternatives in terms of that criterion. Elements of this matrix are calculated by Eq. (4) [26]:

$$C_k(a_1, a_2) = \begin{cases} \frac{g_{ka_1} + p_{ka_2} - g_{ka_2}}{p_{ka_2} - q_{ka_2}} & if\ q_{ka_2} < g_{ka_2} - g_{ka_1} < p_{ka_2} \\ 1 & if\ g_{ka_2} - g_{ka_1} \leq q_{ka_2} \\ 0 & if\ p_{ka_2} < g_{ka_2} - g_{ka_1} \end{cases} \quad (4)$$

Step 4: Constructing the total concordance matrix: Once the partial concordance matrices are constructed for all criteria, the total concordance matrix (C) is obtained by weighted averaging using Eq. (5) [27]:

$$C(a_1, a_2) = \frac{\sum_{k=1}^{n} w_k c_k(a_1, a_2)}{\sum_{k=1}^{n} w_k} \quad (5)$$

Step 5: Constructing the partial discordance matrix for every criterion: Similar to the step 3, the obtained decision matrix and thresholds are used to form the discordance matrix (d_k) for each criterion using Eq. (6) [27, 28]:

$$d_k(a_1, a_2) = \begin{cases} \frac{g_{ka_1} + p_{ka_2} - g_{ka_2}}{v_{ka_2} - p_{ka_2}} & if\ p_{ka_2} < g_{ka_2} - g_{ka_1} < v_{ka_2} \\ 1 & if\ v_{ka_2} < g_{ka_2} - g_{ka_1} \\ 0 & if\ g_{ka_2} - g_{ka_1} \leq p_{ka_2} \end{cases} \quad (6)$$

Step 6: Constructing the total discordance matrix: The total discordance matrix (D) is obtained by weighted averaging using Eq. (7) [24, 25]:

$$D(a_1, a_2) = \frac{\sum_{k=1}^{n} w_k d_k(a_1, a_2)}{\sum_{k=1}^{n} w_k} \quad (7)$$

Step 7: Constructing the credibility (or outranking degree) matrix: The credibility matrix (S), which expresses the credibility of perceived superiority of alternative a_1 over alternative a_2 is formed by merging the total concordance matrix (C) with the total discordance matrix (D) using Eq. (8) [26, 27].

$$S(a_1, a_2) = \begin{cases} C(a_1, a_2) & if\ d_k(a_1, a_2) \leq C(a_1, a_2) \\ C(a_1, a_2). \prod_{k \in J(a_1, a_2)} \frac{1 - d_k(a_1, a_2)}{1 - C(a_1, a_2)} \end{cases} \quad (8)$$

Where $J(a_1, a_2)$ represents those indices in which $d_k(a_1, a_2) > C(a_1, a_2)$.

Step 8: Constructing the final comparison matrix: Having the credibility matrix S, the indices λ and S (λ) are calculated using Equations (9) and (10), respectively [28].

$$\lambda = \max(S) \quad (9)$$

$$S(\lambda) = \alpha - \beta\lambda \quad (10)$$

The final comparison matrix (T) is then formed using Eq. (10) [26, 27].

$$T(a_1, a_2) = \begin{cases} 1 & if\ S(a_1, a_2) \leq \lambda - S(\lambda) \\ 0 & any\ thi\ ngel\ s\ e \end{cases} \quad (11)$$

Step 9: Ranking: Once the final comparison matrix is constructed, alternatives can be sorted from best to worst to determine their final ranking [26, 29].

3.2. Promethee method

PROMETHEE is a group of multi-criteria decision-making models introduced and developed by Brans and Vincke [18]. This group consists of six techniques: PROMETHEE I for partial ranking of alternatives, PROMETHEE II for the complete ranking of discrete alternatives, PROMETHEE III, where preference and indifference relations are defined based on mean and standard deviation of preference indices, PROMETHEE IV, which can be used for unlimited and continuous alternatives, PROMETHEE V for selection of alternatives according to a set of constraints, and PROMETHEE VI, which tries to emulate the approach of human brain to selection [18, 30, 31]. PROMETHEE III and IV have been developed specifically for ranking based on the interval-oriented and the continuous solution spaces, respectively, and cannot be effectively employed for discrete alternatives [18].

Similar to the most of ranking methods, this method starts with a decision matrix of size m×n, where m and n are the number of alternatives and criteria, respectively. In the remainder of the brief description provided for this method, a and b denote the alternatives under evaluation, $g_j(a)$ denotes the element concerning alternative j and criterion j, and P, I and R denote the preference, indifference and incomparability of alternative, respectively. For every a and b, we have Equations (12), (13) and (14) [32]:

$$\begin{cases} \forall j: g_j(a) \geq g_j(b) \\ \exists k: g_k(a) > g_k(b) \end{cases} \leftrightarrow aPb \quad (12)$$

$$\forall j: g_j(a) = g_j(b) \leftrightarrow aIb \quad (13)$$

$$\begin{cases} \exists j: g_j(a) > g_j(b) \\ \exists k: g_k(b) > g_k(a) \end{cases} \leftrightarrow aRb \quad (14)$$

In this method, the parameters expressed the relative importance of criteria (their weights) are typically set by decision-makers [33]. This ranking technique consists of pairwise comparison to the alternatives with emphasis on their numerical difference when compared to other criterion. In this comparison, small differences will be assigned with small preference values. If the difference is insignificant, two alternatives will be considered equal in terms of that criterion, and the bigger the difference, the larger will be the preference score to be assigned to the better alternative. It should be noted that preference scores of this method range between 0 and 1 [18, 27]. To facilitate the operations for decisions of the different nature, Brans and Vincke have provided 6 type of preference function P(d) expressed by Equations (15) to (20) [34].

Type I: Usual Criterion $P(d)=\begin{cases} 0 & d=0 \\ 1 & |d|=1 \end{cases}$ (15)

Type II: U-shape Criterion $P(d)=\begin{cases} 0 & |d| \leq q \\ 1 & |d| > q \end{cases}$ (16)

Type III: V-shape Criterion $P(d)=\begin{cases} \frac{|d|}{p} & |d| \leq p \\ 1 & |d| > p \end{cases}$ (17)

Type IV: Level Criterion $P(d)=\begin{cases} 0 & |d| \leq q \\ 0.5 & q < |d| \leq p \\ 1 & |d| > p \end{cases}$ (18)

Type V: V-shape Criterion with indifference criterion

$$P(d)=\begin{cases} 0 & |d| \leq q \\ \frac{|d|-q}{p-q} & q < |d| \leq p \\ 1 & |d| > p \end{cases} \quad (19)$$

Type VI: Gaussian Criterion $P(d)=1-e^{(-\frac{d^2}{2\sigma^2})}$ (20)
where σ is standard deviation

Typically, the first two functions are used for the nominal criteria and others are used for criteria of higher scales. One also needs to determine the preference threshold p (i.e. the smallest difference that represents the certain preference of one alternative over another), indifference threshold q (i.e. the greatest negligible difference), and s, which is usually between p and q, and is used only in the VI function [34]. The preference of alternatives a and b based on criteria j with weight (Wj) is obtained from Eq. (21) [31, 32].

$$\begin{cases} \pi(a,b) = \frac{\sum_{j=1}^{k} w_j p_j(a,b)}{\sum_{j=1}^{k} w_j} \\ \pi(b,a) = \frac{\sum_{j=1}^{k} w_j p_j(b,a)}{\sum_{j=1}^{k} w_j} \end{cases} \quad (21)$$

Where $\pi(a,b)$ is the preference of a-b based on criteria, and $\pi(b,a)$ expresses the opposite. The net preference of alternative a-b is therefore calculated using Eq. (22) [35].

$$\emptyset(a) = \pi(a,b) - \pi(b,a) \quad (22)$$

For the general state where decision matrix is larger than 2×2, alternative a will be compared with all other alternatives, and the positive and negative outranking flows of this alternative will be given by Equations (23) and (24), respectively [31].

Positive outranking flow: $\emptyset^{+}(a) = \frac{1}{n-1}\sum_{x\in A}\pi(a,x)$ (23)

Negative outranking flow: $\emptyset^{-}(a) = \frac{1}{n-1}\sum_{x\in A}\pi(x,a)$ (24)

In these equations, A is the final comparison matrix, $\emptyset^{+}(a)$ is the score by which alternative a outranks other alternatives, and $\emptyset^{-}(a)$ is the score by which alternative a is outranked by other alternatives. Finally, the net score of alternative a is given by Eq. (25) [34, 35].

$$\emptyset(a) = \emptyset^{+}(a) - \emptyset^{-}(a) \quad (25)$$

If $\emptyset(a) > \emptyset(b)$, then a is preferred to b, or in other words aPb. The preference relations of all alternatives in terms of every criterion are determined similarly.

3.3. Weight assignment by the entropy method

In multi-criteria decision making problems, weight of a criterion is a factor representing its relative importance in the problem. One method of weighting the criteria is to use the Shannon entropy. The term of Entropy (generally meaning disorder) was first introduced by Rudolph Clausius in 1948 in the field of thermodynamics [36]. Later, Shannon extended this concept to the field of information and laid the groundwork for its extensive use in other fields such as engineering and management. This method is particularly useful for evaluating the weights of decision-making criteria that are defined as a complete matrix [37]. In the Entropy method, criteria are weighted according to the dispersion of alternatives when compared in terms of each individual criterion. In other words, the greater dispersion in a criterion, the more important [38]. In the Entropy method, for the decision matrix of size m×n, where m is the number of alternatives ($A_1 \ldots A_m$) and m is the number of criteria

($C_1 \ldots C_n$), criteria weights can be calculated by following the procedure described below [37-40]:

1- Normalizing the decision matrix by dividing each element by the sum of the elements in the corresponding column (Eq. (26)).

$$\emptyset_{i\,j} = \frac{a_{i\,j}}{\sum_{i=1}^{m} a_{i\,j}} \quad (26)$$

where $\emptyset_{i\,j}$ is the normalized value of element concerning alternatives i and j.

2- Calculating the entropy of alternative j by Eq. (27):

$$En_j = -\beta \sum_{i=1}^{m} P_{i\,j} \ln P_{i\,j} \quad (27)$$

Where β is given by Eq. (28).

$$\beta = \frac{1}{\ln(m)} \quad (28)$$

3- Calculating the entropy degree (d) using Eq. (29):

$$d_j = 1 - E_j \quad ; \forall j \quad (29)$$

4- Calculating the criteria weights using Eq. (30):

$$W_j = \frac{d_j}{\sum_{j=1}^{n} d_j} \quad (30)$$

3.4. Criteria involved with the construction of wind-powered seawater desalination plant

The site of the wind farm dedicated to the seawater desalination plant must be located with the objective of maximization of the electricity output and minimization of costs and risks. Thus, before claiming confidently that a location is best for this purpose, the candidate locations must be evaluated in terms of involved factors including wind power density, economic feasibility, topographic conditions, rate of natural disasters, population, and distance of the site from the plant. The following subsections provide a brief review of the involved criteria.

3.4.1. Wind power density

One criterion that positively affect the suitability of an area for construction of a wind farm is the wind power density, which represents and depends on the wind velocity, air pressure and temperature. In this study, wind power density is calculated by the Weibull distribution function, which is one of the most frequently used methods for this purpose. The general relationship of the probability density function of Weibull distribution is presented in Eq. (31) [41]:

$$f(v) = \left(\frac{k}{c}\right) * \left(\frac{\bar{V}}{c}\right)^{k-1} * \left(e^{-(\frac{\bar{V}}{c})^k}\right) \quad (31)$$

Where f(v) and $\bar{V}$ denote the probability density function and the mean wind velocity, respectively. Wind velocity varies noticeably with elevation, so wind velocity at the height of turbine rotor is obtained using the wind profile power law (Eq. (32)) [41]:

$$V_2 = V_1 \left(\frac{H_2}{H_1}\right)^{\alpha} \quad (32)$$

Where V_2 is the wind velocity at the desired height (H_2) and V_1 is the recorded wind velocity at the height of H_1. α is given by Eq. (33) [42]:

$$\alpha = \frac{[0.37 - 0.088\ln(V_1)]}{[1 - 0.088\ln(\frac{H_2}{10})]} \quad (33)$$

Eq. (31) contains two constants c and k, which need to be determined by Equations (34) and (35) [42]:

$$k = \left(\frac{\sigma_v}{\bar{v}}\right)^{-1.086} \quad (34)$$

$$c = \frac{\bar{v}}{\Gamma * (1 + \frac{1}{k})} \quad (35)$$

Where σ_v and Γ denote the standard deviation of wind velocity and the gamma function, respectively. Γ can be obtained from Eq. (36) [43]:

$$(x) = \int_0^{\infty} e^{-u} u^{x-1} dx \; \Gamma \quad (36)$$

Wind power is calculated using Eq. (37) [43]:

$$P(v) = \frac{1}{2} \rho A v^3 \quad (37)$$

Where ρ is the density of ambient air and is estimated by Eq. (38) [43]:

$$\rho = \frac{\bar{P}}{R_d \bar{T}} \quad (38)$$

$\bar{P}$ and $\bar{T}$ denote the mean air pressure in Pascal and the mean air temperature in Kelvin, respectively. R_d is the gas constant for dry air, which equals 287 J/kg.K [44]. In this study, wind power density, as the most important criterion involved with site location, is assumed irrespective of turbine type, and estimated only according to the area created by rotation of turbine blades (A) as expressed by Eq. (39):

$$\frac{P}{A} = \int_0^{\infty} \frac{1}{2} \rho v^3 f(v) dv = \frac{1}{2} \Gamma \rho c^3 (1 + \frac{3}{k}) \quad (39)$$

3.4.2. Topographic condition

Another criterion involved with the site location is the geological condition of the site which depends on the factors such as the area of available flat land without tree cover, geotechnical suitability, and ease of access. In this study, this criterion is estimated using the Google aerial maps and with the help of experts on this field. To calculate the area of usable and available coastal land, we draw a semi-circle centered at candidate site of desalination plant on the coastline (on the land side) and with a 10 km radius (since the studied islands are small in area, 10 km radius is chosen to make sure that the results are comparable; other studies may use larger or smaller radii for this purpose); the area of unsuitable regions are then deducted from the area of this semi-circle (3.14×10×10×0.5=157). The representing value of the alternative in this criterion is calculated by the first selecting a few suitable areas for the wind farm (according to the chosen location for desalination plant on the coastline), calculating the usable area for each location, and finally averaging these areas to determine a capable value of representing the alternative (Eq. (40)).

$$S_{Totl} = \frac{\sum_{i=1}^{n} S_i}{n} \quad (40)$$

A region with the higher average usable area is considered being more topographically suitable for construction of the wind-powered seawater desalination plant.

3.4.3. Distance

Another involved factor is the distance of the site of wind turbines from the coastline (desalination site), as closer this site is to the coastline, the lower will be the energy transmission losses and the consumption of line construction materials. To calculate this criterion, the suitable wind sites (if there are over 1) within a semi-circle centered at the desalination site and with a 10 km radius are selected, and their average distance from the coastline (desalination site) is estimated. The resulting figure is used as the representative alternative in this criterion.

3.4.4. Economic criteria

The most important criterion that needs to be considered before the start of any public or private project is the economic feasibility, which involves sub-criteria such as cost of land, cost of infrastructure and preparation, and cost of skilled labor. Obviously, this criterion and profitability of the project are the factors deciding the attractiveness of investment, so all financial aspects of the project need to be considered before other efforts. In this study, the cost per square meter of land is considered as the representative of alternatives in this criterion, since costs pertaing to labor force, facilities and maintenance are The same everywhere in Iran.

3.4.5. Rate of natural disasters

The constructed desalination plant and wind farm are expected to have the longest possible lifetime, and for achieving this goal, the factors that reduce this lifetime need to be identified and minimized. One of the factors that can negatively affect the lifetime of these facilities is the natural disasters such as massive floods and powerful earthquakes. The probability of these disasters is estimated using the long-term data on previous events in the area.

The natural disasters that can have the devastating impact on the wind turbines and seawater desalination plants are floods, earthquakes, tsunamis and dust storms. Dust storm is included because of its great damage to turbine blades and tsunamis because of its devastating effect on the shore facilities (seawater desalination system).

The higher probability of natural disasters in ports and coastlines, the lower should be their preference level, so this criterion has a negative impact. The representative of alternatives in this criterion is determined by averaging the obtained values for these four events. First, the probability of each event needs to be estimated separately. This estimation is done based on the worth of 70 years of natural disaster records available on the website [45]. Considering the type of infrastructure required for wind-powered seawater desalination plant, earthquakes weaker than 7 on the Richter scale will have no significant impact on its facilities and equipment. Therefore, all estimations for all areas are performed using the records of earthquakes stronger than 7 on the Richter scale.

According to the nature of natural disasters such as floods, tsunamis and earthquakes, their probability follows the Poisson distribution function expressed by Eq.(41) [46]:

$$f(x) = \frac{e^{-\lambda}\lambda^{x}}{x!} \quad (41)$$

Where λ is the average frequency of natural disasters within the specified period and x is the frequency of natural disasters for which the probability of occurrence in the desired period is being calculated. Since turbines are expected to have a lifetime of about 25 years [9], we calculate the probability of occurrence of 1 powerful disaster event over the next 25 years.

The probability of dust storms is estimated by normal approximation to the binomial distribution. For this purpose, the collected data is used to calculate the probability of dusty days in one year, and this number is considered as p of the binomial distribution. Then, the total number of days in the turbine lifetime period (25 years including leap years) is considered as n of the binomial distribution. For normal approximation of the binomial distribution, the mean (μ) and standard deviation (σ) are estimated using Equations (42) and (43), respectively.

$$\mu = np \quad (42)$$

$$\sigma = \sqrt{np(1-p)} \quad (43)$$

For each of the four natural disasters, the probability of at least 1 occurrence over the 25 years of facility lifetime is calculated, and finally, these probabilities are averaged to obtain a representative for alternatives in this criterion.

3.4.6. Population

The last criterion to be considered in this study is the population of each region. This criterion is selected because of its effect on the demand for fresh water and thus its involvement with the magnitude of energy needed for the project. This criterion is considered to have a positive impact on suitability, as supplying water to more populous areas is a higher priority.

4. CALCULATIONS

In this section, the selected criteria are calculated and then weighted by the entropy method. Next, alternatives are ranked using the ELECTRE III method with the help of EXCEL software. Lastly, the results are validated by the PROMETHEE II method.

4.1. Criteria

In this study, only four of the six involved criteria, i.e. wind power density, topographic conditions, wind farm-coastline distance, and the rate of natural disasters needed to be calculated, as the other two, i.e. price per square meter of land and population could be obtained directly from the available statistics and records.

To estimate the wind power density in the studied regions, the 3-hour meteorological data pertaining to a 15-year period (from 2001 to 2015), which was collected from the Meteorological Organization of Iran, was analyzed. The preliminary calculations showed that Qeshm Island and Lengeh port are the top two alternatives in this ranking. The wind power densities of Qeshm Island and Lengeh port are 220.6 w/m^2.yaer and 220.6 w/m^2.yaer, respectively. On the other hand, Lavan Island's wind power density of 142.1 w/m^2.yaer is the lowest suitable alternative in terms of this criterion.

For comparison in terms of topographic condition, for every alternative, five coastal points with apparent suitability for construction of desalination facility were selected. The usable areas were then determined by drawing the semi-circles and deducting the areas of regions unsuitable for wind farm from the area of respective semi-circles. Finally, the average of these five usable areas was calculated as the representative of alternatives in this criterion. The calculation results show that Kish Island and Mahshahr port with the usable land areas of respectively 243 km^2 and 224 km^2 are the first and second ranking alternatives in this regard. At the bottom of this ranking is Jask port with usable land area of 76 km^2.

To estimate the wind farm-coastline distance criterion, the same five coastal points were again selected for each alternative and 10 suitable sites (for wind farm) within 10 km distance of these points were identified. Finally, the average distance of these sites from the coastline was calculated as the representative of alternatives in this criterion. The calculation results showed that in this criterion, the bottom ranking alternative was Jask port with the average distance of 9.4 km (the longest average distance and thus the least favorable result), while the top ranking alternative was Qeshm Island with the average distance of 3.92 km.

TABLE 2. Values of the involved criteria with the ranking of areas

	C1: Wind power	C2: Topographic	C3: Distance	C4: Economic	C5: Disaster	C6: Population
A1: Mahshahr	156.4	112	6.45	340,000	0.56	173,877
A2: Deilam	144	104	5.65	140,000	0.62	27,896
A3: Chark	196.2	53	8.63	50,000	0.51	6,248
A4: Jask	163.1	46	9.4	145,000	0.46	30,134
A5: Khamir	198.5	71	7.14	105,000	0.52	15,853
A6: Deir	185.3	63	9.1	120,000	0.70	22,256
A7: Ganaveh	167	91	8.34	185,000	0.59	68,596
A8: Lengeh	217.6	87	9.61	160,000	0.61	29,654
A9: Bandar Abbas	176.1	81	8.92	650,000	0.50	460,812
A10: Chabahar	162.9	57	5.95	390,000	0.46	128,243
A11: Kish	200.5	122	4.12	310,000	0.56	32,846
A12: Hormoz	203.4	46	5.5	190,000	0.49	24,732
A13: Qeshm	220.6	102	3.92	240,000	0.54	31,257
A14: Abumusa	171.3	63	6.88	270,000	0.56	4,232
A15: Lavan	142.1	103	4.32	90,000	0.50	3,968

The last calculated criterion was the probability of at least one natural disaster in the next 25 years, which was obtained according to the statistics of disaster events in the last 70 years, based on the available records on the website [45]. The results showed that Deir port has the highest probability of at least one incident of flood, earthquake, tsunami and dust storm in the next 25 years, while the lowest probability of natural disaster (0.46%) belongs to Jask and Chabahar ports. Table 2 shows the results regarding the involved criteria with the ranking of studied areas.

4.2. Weighting of criteria by the entropy method

In weight assignment using the entropy method, criteria were weighted based on the dispersion of alternatives when compared in terms of each individual criterion (the more dispersed alternatives, the greater weight). After normalizing the decision matrix, it was found that dispersion value was so greater in the criterion “population” than any other criteria that the entropy method calculates its weight to 0.733. This was entirely because of the significant difference between the population of BandarAbbas (the most populous alternative with about 460,812 citizens) and Lavan Island (the least populous alternative with about 3,968 inhabitants). The lowest dispersion value was obtained for the criterion of “rate of natural disasters”, and its corresponding weight was calculated to be 0.006. Likewise, weights of the criteria wind power density, topographic condition, coastline-wind farm distance, and economic feasibility were calculated to be 0.009, 0.046, 0.036 and 0.17, respectively

4.3. Ranking of alternatives using the ELECTRE method

After determining and weighting the involved criteria with the ranking of alternatives in terms of suitability for construction of wind-powered seawater desalination plant was determined using the ELECTRE III method. Table 3 shows the credibility matrix S representing the importance of alternatives with respect to each other. For example, the figure 0.794 in the first row and the second column indicates that alternative 2 has a credibility (or outranking) level of 0.794 with the respect to alternative 1, while alternative 1 has a credibility (or outranking) level of 1-0.794=0.206 with respect to alternative 2.

TABLE 3. Credibility matrix S

	A1	A2	A3	A4	A5	A6	A7	A8	A9	A10	A11	A12	A13	A14	A15
A1	0	0.794	0.815	0.815	0.815	0.821	0.821	0.821	0.252	0.949	0.739	0.779	0.779	0.815	0.788
A2	0.206	0	0.815	0.252	0.815	0.821	0.252	0.252	0.252	0.252	0.17	0.949	0.216	0.985	0.788
A3	0.185	0.185	0	0.261	0.176	0.221	0.185	0.212	0.215	0.179	0.176	0.216	0.176	0.918	0.912
A4	0.185	0.748	0.739	0	0.739	0.739	0.176	0.945	0.176	0.185	0.176	0.909	0.176	0.909	0.748
A5	0.185	0.185	0.824	0.261	0	0.267	0.221	0.212	0.215	0.225	0.176	0.216	0.176	0.964	0.742
A6	0.179	0.179	0.779	0.261	0.733	0	0.179	0.206	0.179	0.225	0.17	0.216	0.17	0.958	0.742
A7	0.179	0.748	0.815	0.824	0.779	0.821	0	0.821	0.252	0.225	0.903	0.949	0.903	0.949	0.742
A8	0.179	0.748	0.788	0.055	0.788	0.794	0.179	0	0.225	0.225	0.179	0.958	0.17	0.958	0.742
A9	0.748	0.748	0.785	0.824	0.785	0.821	0.748	0.775	0	0.788	0.739	0.779	0.739	0.794	0.742
A10	0.051	0.748	0.821	0.815	0.775	0.775	0.775	0.775	0.212	0	0.739	0.785	0.739	0.775	0.748
A11	0.261	0.83	0.824	0.824	0.824	0.83	0.097	0.821	0.261	0.261	0	0.815	0.779	0.824	0.824
A12	0.221	0.051	0.784	0.091	0.784	0.784	0.051	0.042	0.221	0.215	0.185	0	0.176	0.954	0.748
A13	0.221	0.784	0.824	0.824	0.824	0.83	0.097	0.83	0.261	0.261	0.221	0.824	0	1	0.824
A14	0.185	0.015	0.082	0.091	0.036	0.042	0.051	0.042	0.206	0.225	0.176	0.046	0	0	0.742
A15	0.212	0.212	0.088	0.252	0.258	0.258	0.258	0.258	0.258	0.252	0.176	0.252	0.176	0.258	0

Next, the final comparison matrix was constructed and alternatives were ranked according to the method described in section 3. In the end, ranking of alternatives in terms of 6 studied criteria was found to be: 1- Qeshm, 2- Deilam, 3- Khamir, 4- Lengeh, 5- Hormoz, 6- Deir, 7- Mahshahr, 8- Ganaveh, 9- Chark, 10- Jask, 11- Kish, 12- Abbas, 13- Chabahar, 14- Abumusa and 15- Lavan.

4.4. Sensitivity analysis

A sensitivity analysis was conducted to measure the impact of each criterion on the ranking. Table 4 shows the sensitivity of ranking to criteria. This table indicates that the criteria “wind power density” and “wind farm-coastline distance” most significantly affect the alternative “Ganaveh”, as disregarding these criteria improves the ranking of this alternative from 8 to 4. It is also seen that the alternative most affected by "topologic condition" is Jask, as disregarding this criterion improves the ranking of this alternative noticeably from 10 to 3. It can also be seen that the alternatives mostly affected by the criteria of "economic feasibility", "natural disasters", and "population" are "Kish" (9 points rise in ranking), "Khamir" (4 points fall in ranking) and again "Kish" (8 point rise in ranking), respectively

TABLE 4. Results of sensitivity analysis

	Ranking before sensitivity analysis	Ranking after elimination of wind power	Ranking after elimination of topographic	Ranking after elimination of distance	Ranking after elimination of economic	Ranking after elimination of disaster	Ranking after elimination of population
A1: Mahshahr	7	6	11	6	3	5	12
A2: Deilam	2	2	4	5	5	2	5
A3: Chark	9	10	6	9	13	9	9
A4: Jask	10	9	3	10	12	10	13
A5: Khamir	3	3	5	2	11	8	1
A6: Deir	6	8	8	7	10	7	10
A7: Ganaveh	8	4	9	4	4	4	8
A8: Lengeh	4	5	7	3	7	3	6
A9: Bandar Abbas	12	12	13	11	6	12	15
A10: Chabahar	13	13	12	13	8	13	14
A11: Kish	11	11	10	12	2	11	3
A12: Hormoz	5	7	2	8	9	6	7
A13: Qeshm	1	1	1	1	1	1	2
A14: Abumusa	14	14	14	14	14	14	11
A15: Lavan	15	15	15	14	15	15	4

4.5. Validation using the PROMETHEE method

Validity of the obtained ranking in the section of 4.3. was evaluated by the PROMETHEE method. Since this study is based on the long-term data, the calculated values for criteria could be assumed to be almost permanent.Based on this assumption, the type I function (Eq. 15) of the PROMETHEE method was used to re-rank the alternatives. In this re-ranking, criteria were weighted by several relevant experts, whose inputs were averaged. Ultimately, the weighs of the criteria wind power density, economic feasibility, topographic condition, natural disasters, population, and coastline-wind farm distance were calculated to be 0.488, 0.069, 0.154, 0.213, 0.033, and 0.043, respectively. After re-ranking by the PROMETHEE method, it was found that Qeshm had maintained the top spot in the ranking. The obtained ranking by the PROMETHEE is as follows: 1- Qeshm, 2- Hormoz, 3- Kish, 4- Lengeh, 5- Khamir, 6- Chark, 7- Bandar Abbas, 8- Jask, 9- Deir, 10- Chabahar, 11- Ganaveh, 12- Abumusa, 13- Lavan, 14- Mahshahr, and 15- Deilam.

5. CONCLUSION

Water scarcity is one of the seriously challenge in some countries around the world. Iran is one of the countries that are experiencing the water shortage caused by reduced precipitation combined with years of excessive utilization of underground water resources. This issue is even more serious in arid and semi-arid central and southern parts of the country. For moving toward the sustainable development in the field of water treatment and energy generation, this study suggests the use of the wind turbine to power a water purification and desalination facility to be constructed in the southern islands and coastal areas of the country.

To maximize the efficiency and lifetime of such wind-powered project, it is essential to start the effort with identification of best sites for implementation. Therefore, different involved criteria with the suitability of a location for such wind-powered seawater desalination project were evaluated in this study. The multi-criteria decision-making method ELECTRE III was then used to rank 10 ports and 5 islands located in southern Iran in this respect. The obtained results from criteria analysis and ranking of alternatives are summarized below.

- After collecting the long-term weather data and calculating the wind power density for every location, it was found that Qeshm Island, Lengeh Port and Hormuz Island with the wind power densities of 220.6, 217.6 and 203.4, respectively and hold the first to third ranks in terms of this criterion.

- For the criterion topographic condition and each alternative, five coastal points with apparent suitability for construction of desalination facility were selected, and then a semi-circle centered at these points and with a 10 km radius was drawn. The average area of topographically suitable regions in these semi-circles were then determined. The results showed that among the 15 studied regions, Kish Island, Mahshahr Port, and Deilam Port hold the top three ranks in terms of this criterion.
- To calculate the concerning criterion of the distance of wind farm from seawater desalination system, the above described semi-circles were again considered, but this time the average distance of 10 sites within each semi-circle from its center was determined. Qeshm, Kish and Lavan Islands with the average distance of 3.92, 4.12 and 4.32 km were found to be the top three sites in this criterion (the shorted distances are better).
- For the concerning criterion of the rate of natural disasters, 4 types of natural disaster, namely flood, earthquake, tsunami and dust storms were considered. After estimating the probability of each event and averaging their values, it was found that the ports Jask and Chabahar had the lowest probability of experiencing such natural events during the next 25 years (facility lifetime).
- According to the great impact of land price on the costs, the economic feasibility criterion was estimated with the price per square meter of land considering as the representative of each alternative in this criterion.
- Ranking of alternatives with the multi-criteria decision-making technique ELECTRE III required criteria to be weighted by other means, so this task was carried using the Entropy method, which weights the criteria based on dispersion of alternatives in each individual criterion. This method found the greatest dispersion in the criterion of "population", and therefore assigned the greatest weight to this particular criterion.
- After determining and weighting the involved criteria with ranking, the studied ports and islands were ranked using the ELECTRE III method. Finally, Qeshm Island was found to be the best location for building a wind-powered seawater desalination plant.
- Validity of above ranking was evaluated by the PROMETHEE method, and this method also placed Qeshm Island at the top of the ranking.

In the end, this study recommended the Qeshm Island as the site of a seawater desalination plant powered by a dedicated wind farm.

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Nomenclature

ELECTRE	
m	The number of criteria
n	The number of alternatives
a_i	The ith alternative
k	The total number of criteria ($1< k < j$)
g_{ka_i}	The related element to the alternative a_i and criterion k
q	Indifference threshold
p	Preference threshold
v	Veto threshold
q_i	Indifference threshold for the i-th alternative
p_i	Preference threshold for the i-th alternative
v_i	Veto threshold for the i-th alternative
c_k	Concordance matrix
w_k	Weighted criterion ($1< k < j$)
d_k	Discordance matrix
D	Total discordance matrix
S	Credibility matrix
C	Total concordance matrix
T	Final comparison matrix
PROMETHEE	
$g_j(a)$	Element pertaing to alternative and criterion jth
P	Preference of alternative
I	Indifference of alternative
R	Incomparability of alternative
a and b	Alternatives under evaluation
P(d)	Preference function
$\emptyset^{+}(a)$	Positive outranking flow
$\emptyset^{-}(a)$	Negative outranking flow
Weight Assignment by the Entropy Method	
$\emptyset_{ij}$	Normalized value pertaining to alternatives i and j
En_j	The entropy of alternative j
d	The entropy degree
Wind Power Density	
f(v)	Probability density function
$\overline{V}$	Mean wind velocity (m/s)
V_1	Wind velocity at the height of H_1 (m/s)
V_2	Wind velocity at the desired height of H_2 (m/s)
α	Coefficient of the power law
c	Scale parameter
k	Shape parameter
σ_v	Standard deviation of wind speed
Γ	Gamma function
ρ	Density of ambient air
$\overline{P}$	Mean air pressure (Pascal)
$\overline{T}$	Mean air temperature (Kelvin)
R_d	Gas constant for dry air (J/kg.K)
A	Area created by rotation of turbine blades (m^2)
Topographic Condition	
S_{Totl}	Total average of suitable areas (m^2)
S_i	The i-th suitable area (m^2)
Rate of Natural Disasters	

λ	Average frequency of natural disasters within the specified period
Wj	Weight of j-th criterion
$\pi(a,b)$	Preference of a to b
$\emptyset\ (a)$	Net preference of alternative a to b
μ	Mean
σ	Standard deviation

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