Desalination technology selection using multi-criteria evaluation: TOPSIS and PROMETHEE-2

P. Vivekh, M. Sudhakar, M. Srinivas* and V. Vishwanthkumar
Mechanical Engineering Department, BITS-Pilani, Hyderabad Campus, Hyderabad, RR District, Telangana State 500078, India

Abstract

In this paper, the need of multi-criteria evaluation (MCE) for a desalination technology selection is emphasized through a case study. Decision context, problem formulation and the relative importance of 11 complete, operational and non-redundant criteria were established which represented the behavior of the MCE problem. TOPSIS and PROMETHEE-2 methods were identified as the appropriate MCE techniques and the five alternatives were evaluated using these methods separately. The respective results indicated that ED was the most applicable technology for the selected community and ranked the usage of electrodialysis, reverse osmosis, vapor compression, multiple effect distillation and multi-stage flash in the decreasing order of priority.

Keywords: desalination; technology selection; community scale; electrodialysis; multi-criteria evaluation; TOPSIS; PROMETHEE-2

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1 INTRODUCTION

The present scenario of increasing population has resulted in the scarcity of potable water. It is estimated that the demand for water will surpass its availability by 56%, and 1.8 billion people will be living in regions of water scarcity by 2025 [1]. According to WHO standards [2], water containing total dissolved salts (TDS) concentrations below 1000 ppm is usually acceptable to consumers, although acceptability may vary according to circumstances. Therefore, an ever-increasing demand and a non-uniform distribution have forced mankind to develop novel methodologies of generating potable water, which are highly energy-intensive processes. Several desalination technologies have been evolved over the years and have been extensively used. The most important techniques of desalination are multi-stage flash (MSF), multiple effect distillation (MED), vapor compression (VC), reverse osmosis (RO) and electrodialysis (ED).

MSF, MED and VC are thermal-based desalination techniques which work on the principle of phase change. MSF process is based on the generation of vapor from sea water due to the flashing action and the process is repeated in different stages by successively decreasing the pressure. In MED, vapors are generated through the absorption of thermal energy by the feed water. The steam generated in one effect can heat the salt solution at the lower pressure and temperature in the next stage. MED and MSF require an external source of heat, like crude oil, natural gas or solar collectors, to warm up the incoming saline water, whereas the energy needed to heat the saline water in the VC method comes from a vapor compressor. Further, VC is classified into thermal vapor compression or mechanical vapor compression depending on the ways of compressing the initial vapor from the saline solution. The other category of industrial desalination processes, RO and ED, involves membranes. RO requires electricity or shaft power to drive the pump that increases the pressure of the saline solution. ED also requires electricity for the ionization of water. Water is cleaned by using suitable membranes located at the two oppositely charged electrodes. Both RO and ED are extensively used for brackish water desalination, but RO alone competes with the other techniques for seawater desalination [3]. Since, majority of these desalination processes use non-renewable source of energy, it is essential to look for technologically efficient desalination techniques or check the feasibility of using renewable energy in these techniques. Figure 1 specifies different possible renewable energy sources which can supply the energy demands of desalination [4].
As these desalination technologies are suitable for many end-user applications such as industrial, community and household activities, the selection of an appropriate desalination technology for a particular application is a difficult exercise. In the next section of this paper, the complexities involved in the selection of a desalination technology for a community-based application would be highlighted. Further, through this case study, the importance and necessity of multi-criteria evaluation (MCE) for desalination technology selection problem would be emphasized. Further, the ‘viability’ of desalination technology would be defined and the desalination technology selection problem would be formulated in MCE environment by identifying the criteria and subcriteria governing the ‘viability’. Methods such as TOPSIS and PROMETHEE-2 would be used for evaluating the ‘viability’ of desalination technology for the selected case study. Finally, basing on the results obtained, the process for finding the best alternative for other end-user applications would be highlighted.

2. COMPLEXITIES IN SELECTION OF DESALINATION TECHNOLOGY: A CASE STUDY

The choice of selecting the best desalination technique for a particular application is extremely difficult as the number of desalination technologies available is overwhelmingly high and every technique stands suitable for many end-user applications. Therefore, in order to assess the complexities involved in the selection of a desalination technology for a particular application, a study was conducted for a community by analyzing its desalination requirement. The selected community, Birla Institute of Technology and Science, Pilani—Hyderabad Campus (BPHC), is an educational institution spread over an area of 200 acres in Hyderabad, India, having 3500 people and houses students, teaching, non-teaching staffs and their families. The campus has many academic departments, hostels, dining halls and faculty quarters where there is a demand for desalinated water. A survey was conducted and the total demand of desalinated water was calculated to be 20–22 m$^3$/day and the TDS of the water sources was found to be 1340 PPM. Currently, the water needs are being met through the ground water resources and municipal water supplies, by treating the input water using various small and independent RO systems to bring down the TDS value from 1340 PPM to different levels as required. However, the survey also indicated the need for having one desalination technology catering the complete demand. Hence, there was a need for the selection of an appropriate technology for this application and subsequently a comparative analysis was performed.

Solar stills, MSF, MED, VC, RO and ED processes were considered for the analysis because of their wide establishment and applicability to handle various types of end-user application across the globe for decades \[5\]. Considering factors such as energy requirements, quality of the treated water, capability of handling feed water, investment, operation and maintenance costs etc., it was seen that solar stills required huge investment ($20,790,000) and area of deployment (66,000 m$^2$) for the production 20–22 m$^3$ of water per day and accordingly, it was eliminated from the analysis due to its infeasibility for an educational institution \[4, 6–10\]. MSF, MED and VC processes were only applicable to desalinate sea water and the community having brackish water as the feed water with 1340 PPM was not feasible for their usage. Moreover, MSF and MED were found economical only for large-scale systems, whereas membrane-based technologies, ED and RO, were found suitable for a wide

![Figure 1. Possible options for renewable energy-based desalination technologies.](https://academic.oup.com/ijlct/article/12/1/24/2527608)
Thus, the problem of selecting appropriate technology for this community was narrowed to the selection in between RO and ED. Extensive literature review was done to perform the comparative study between these two processes. Factors such as consumption of energy, osmotic pressure requirement, scaling potential, quality of feed water, molecular weight of the solution and noise generation were used for comparison. Based on the energy consumption and osmotic pressure requirement, ED was relatively advantageous as it consumed less energy [13]. According to factors such as scaling potential and molecular weight, ED process was only suitable for removing low molecular components from water which was a disadvantage when compared with RO. However, the ground water reports near the community classified the ground water as having low molecular compounds [14, 15]. Subsequently, ED was chosen over RO as a suitable process for this community. The comprehensive details of this entire analysis are presented by Srinivas et al. [16].

However, this case study narrates a rudimentary and simplified method of selection of an appropriate desalination technique. Therefore, to corroborate the results drawn and to make an affirmative conclusion to the given problem, a scientific/mathematical approach needs to be adopted. Also, there was a need to obtain a mathematical index to rank the desalination technologies because the data required for location, demand specification and technology were not extensively available in the literature for all types of applications [17]. As observed from the above case study, the desalination technology selection is governed by several factors which evolve from a host of various scientific, engineering, cultural, environmental and other considerations. Thus, the evaluation of a desalination technology is viewed as an MCE problem.

3 DESALINATION TECHNOLOGY SELECTION PROBLEM IN MCE ENVIRONMENT

The methodological steps for the selection of best suitable desalination technology from a set of available alternatives in MCE environment are described in Figure 2 [18–20]. The following sections describe these steps in detail and emphasize the role played by these steps in decision-making.

3.1 Decision context, identification of alternatives and criteria

The need for desalination was surveyed through the case study and ‘the selection of most appropriate desalination technology’ was identified as the decision context. The alternatives were selected as MSF, MED, VC, RO and ED and they were represented in the analysis as A1, A2, A3, A4 and A5, respectively. Since, the decision context directly depends on the factors affecting the problem, the decision criteria need to be selected with utmost care. Here, the decision criteria can be viewed as any characteristic, viz. yield, cost, energy requirement etc., related to the desalination technology that directly/indirectly affects the functionality of the technology. Some of these criteria have to be maximized and some have to be minimized simultaneously for obtaining a mathematical/scientific index called ‘viability’.

Hence, if \( v_1, v_2, v_3 \ldots \) are various criteria that affect the selection of a desalination technology, then the ‘viability’, \( V \), of the desalination technology selection problem is defined as

\[
V = f(v_1, v_2, v_3 \ldots v_n)
\]

where \( n \) is the number of criteria to be taken into account. A desalination technology is said to have an optimum ‘viability’ if all the criteria considered are simultaneously optimized.

After referring to various literature sources [12, 21–23], initially a comprehensive list of 25 criteria was prepared. Some of those criteria were ‘treated water quality’, ‘life time of technology’, ‘maximum input capacity’, ‘minimum input capacity’, ‘operation cost’, ‘material cost’, ‘installation cost’, ‘consumption of electrical energy and thermal energy’ and so on. However, as per the classical MCE theories, the criteria selection process must include only those criteria which are complete, operational, non-redundant and should be minimum in number [24]. Accordingly, criteria such as ‘maximum input capacity’ and ‘minimum input capacity’ were clubbed together as ‘scalability’ and likewise 11 major criteria (C1–C11) were obtained and

![Flowchart showing the methodology adopted in MCE environment.](https://academic.oup.com/ijlct/article/12/1/24/2527608)
were vetted with the experts. Further, in order to have concise representation of the behavior of the desalination technology selection problem, criteria of similar types were grouped together viz. technical (G1), economic (G2), social (G3) and behavioral and energy (G4). The decision hierarchy of the desalination technology selection in MCE environment is represented in Figure 3 and the criteria necessary for the problem along with its nature (maximization or minimization) are represented in Table 1.

3.2 Estimation of weights of criteria
For analyzing alternatives with respect to criteria, relative importance of the criteria with respect to each other must be calculated. As the literature does not provide the details regarding the relative importance, in this paper, priorities of the criteria have been synthesized by following the Saaty’s nine-point scale of relative importance which is mentioned in Table 2 [25].

Each criterion was compared pairwise with the other and the relative importance value was obtained. Here, pairwise comparison of each criterion was done by three decision makers and the average values of their responses have been tabulated in Table 3.

The eigenvector approach using the power method was adopted to compute the priorities of the criteria and to obtain their relative importance values. These values were then normalized using the below equation.

\[ v_j(a) = \frac{f_j(a)}{\sum f_i(a)}, \quad j = 1, 2, \ldots, 11 \]  

where \( v_j(a) \) indicates the normalized value of the \( j \)th criterion and \( f_j(a) \) the weight of the \( j \)th criterion before normalization and these values have been represented in Table 4.

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Table 1. Definition of the criteria along with the nature and units.

| Group                | Notation | Criteria                  | Definition                                                                 | Qualitative | Units | Max/min |
|----------------------|----------|---------------------------|---------------------------------------------------------------------------|-------------|-------|---------|
| Technical (G1)       | C1       | Lifetime                  | Life time of the technology till the major replacement                    | —           | Years | Max     |
|                      | C2       | Scalability               | Ratio of the difference of max and min capacity                           | —           |       |         |
|                      | C3       | Adaptability              | Max. input water salinity that the technology can handle                  | —           | PPM   | Max     |
|                      | C4       | Water recovery            | Product water relative to input water flow                                | —           | l/l   | Max     |
|                      | C5       | Treated water quality     | Salinity of the product water                                             | —           | PPM   | Min     |
| Economic (G2)        | C6       | Capital cost              | Purchase of Mechanical Equipment and installations                       | —           | Unit/l| Min     |
|                      | C7       | Maintenance cost          | Cost of operations and maintenance                                        | —           | Unit/l| Min     |
| Social and behavioral (G3) | C8    | Acceptance of desalination technology | Ease of acceptance of the desalination technology                         | Yes         | —     | Max     |
|                      | C9       | Degree of complexity      | Skill required for operation                                              | Yes         | —     | Min     |
| Energy and environment (G4) | C10   | Consumption of energy     | Amount of energy consumed per liter                                        | —           | kWh/m³| Min     |
|                      | C11      | Degree of usage of green energy | Level or extent of using green energy                                     | Yes         | —     | Max     |

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Figure 3. Decision hierarchy of the desalination technology selection.
Table 2. Saaty’s nine-point scale of relative importance.

| Stage of scale | Definition | Characteristics |
|----------------|------------|-----------------|
| 1  | Equal importance | Two activities contribute equally |
| 3  | Moderate importance of one over another | Experience and judgment moderately favor one activity over another |
| 5  | Strong importance | Experience and judgment strongly favor one activity over another |
| 7  | Very strong importance | An activity is strongly favored and its dominance demonstrated in practice |
| 9  | Extreme importance | The evidence favoring one activity over another is of the highest possible order of affirmation |
| 2, 4, 6, 8 | Intermediate values between the two adjacent judgments | When compromise is needed |
| Reciprocals | — | If activity 1 has one of the above numbers assigned to it when compared with activity 2, then activity 2 has the reciprocal value when compared with activity 1. Thus, the lowest limit in the scale is 1/9 being reciprocal of 9 |

Table 3. Matrix on the relative importance of the criteria.

|   | C1     | C2     | C3     | C4     | C5     | C6     | C7     | C8     | C9     | C10    | C11    |
|---|--------|--------|--------|--------|--------|--------|--------|--------|--------|--------|--------|
| C1 | 1      | 3      | 4      | 7      | 0.143  | 0.2    | 0.333  | 7      | 7      | 0.125  | 3      |
| C2 | 0.333  | 1      | 0.5    | 0.333  | 0.143  | 0.143  | 0.143  | 4      | 0.333  | 0.143  | 0.25   |
| C3 | 0.25   | 2      | 1      | 1      | 0.2    | 0.143  | 0.2    | 7      | 5      | 0.143  | 1      |
| C4 | 0.143  | 3      | 1      | 1      | 0.25   | 0.143  | 0.25   | 4      | 5      | 0.143  | 3      |
| C5 | 7      | 7      | 5      | 4      | 1      | 1      | 2      | 7      | 7      | 0.5    | 6      |
| C6 | 5      | 7      | 7      | 7      | 1      | 1      | 5      | 8      | 5      | 0.5    | 5      |
| C7 | 3      | 7      | 5      | 4      | 0.5    | 0.2    | 1      | 6      | 3      | 0.2    | 3      |
| C8 | 0.143  | 0.25   | 0.143  | 0.25   | 0.143  | 0.125  | 0.167  | 1      | 0.2    | 0.111  | 0.2    |
| C9 | 0.143  | 3      | 0.2    | 0.2    | 0.143  | 0.2    | 0.333  | 5      | 1      | 0.143  | 0.2    |
| C10| 8      | 7      | 7      | 7      | 2      | 2      | 5      | 9      | 7      | 1      | 7      |
| C11| 0.333  | 4      | 1      | 0.333  | 0.167  | 0.2    | 0.333  | 5      | 5      | 0.143  | 1      |

Table 4. Weights of each criterion after normalization.

| Criteria | Weights |
|----------|---------|
| C1       | 0.085   |
| C2       | 0.019   |
| C3       | 0.039   |
| C4       | 0.044   |
| C5       | 0.176   |
| C6       | 0.196   |
| C7       | 0.100   |
| C8       | 0.012   |
| C9       | 0.024   |
| C10      | 0.265   |
| C11      | 0.040   |

3.3 Selection of aggregation techniques for evaluation

The presence of different characteristics in every MCE problem stimulated the evolution of several different aggregation methods. These methods include weighted sum, preference ranking organization method for enrichment evaluation (PROMETHEE), multi-attribute utility theory, analytical hierarchical process (AHP), Technique for Order of Preference by Similarity to Ideal Solution (TOPSIS), different ELECTRE methods, multi-objective programming, fuzzy logic-based methods etc. The presence of many methods is also disadvantageous as choosing one method out of all is itself a multi-criteria task.

3.4 Data collection and payoff matrix

The information pertaining to each criterion for all the five alternatives were not found in literature as some of the criteria were qualitative. While the data pertaining to all the quantitative criteria for all five alternatives were obtained from various literature sources [4, 9, 12, 34, 35], a survey was conducted to obtain
the information related to qualitative criteria. The data collected were in a scale of 1–5, thereby converting the qualitative criteria into quantitative. The payoff matrix was developed from the above sources and has been represented in Table 5. Since, the data for each criterion correspond to different units; the payoff matrix was normalized using Equation (2) and is represented in Table 6.

In the next section, the calculations involved in obtaining the best alternative and determination of viability index using TOPSIS and PROMETHEE-2 will be discussed in detail.

4 EVALUATIONS AND RESULTS

Several software were available in the market for TOPSIS and PROMETHEE-2 evaluations like TOPSIS 3.1, Fuzzy TOPSIS 3.0, Visual PROMETHEE 1.4, PROMCALC, DECISIONLAB etc. which can be used for various types of applications in addition to desalination. Despite having such sophisticated software, we used our own programs developed using MS EXCEL and matLAB where we supplied the variables and performed the calculations pertaining to desalination requirements alone. Thus, the tool which we have designed can be used for any type of desalination requirement without having to tediously work on defining criteria, alternatives and formation of payoff matrix. Just by manipulating few variables (discussed later in this section) in our program, any user can find out the best possible desalination technology for any type of desalination application which he/she is interested in. In the forthcoming subsections, the viability will be evaluated first using TOPSIS and then using PROMETHEE-2. The results obtained using these aggregation methods will be compared and a conclusion about the merits of using each method will be emphasized.

4.1 Evaluation using TOPSIS: methodology

TOPSIS is based on the principle that the chosen alternative should have the shortest distance from the ideal solution and the farthest from the negative ideal solution [36, 37]. In this problem, the ideal solution is the selection of best alternative and the non-ideal solution is the technology which is not suitable for the application. The methodology of using TOPSIS consists of the following steps.

1. The weighted normalized payoff matrix needs to be obtained by multiplying the normalized decision matrix, i.e. Table 6 with the weights of the criteria in Table 4.
2. The nature of every criterion must be converted to maximization.
3. The positive ideal solution ($f_j^*$), i.e. the most ideal desalination technology solution with respect to the $j$th criterion and the negative ideal solution ($f_j^{**}$), i.e. the least ideal alternative with respect to the $j$th criterion is determined for all the 11 criteria.
4. The distance of each alternative from positive ideal ($D_a^+$) and negative ideal ($D_a^-$) values is calculated using the below equations:

$$D_a^+ = \sqrt{\sum_{j=1}^{I} (f_j(a) - f_j^*)^2} \quad (3)$$

$$D_a^- = \sqrt{\sum_{j=1}^{I} (f_j(a) - f_j^{**})^2} \quad (4)$$

1. The closeness coefficient of each alternative ($C_a$) relative to its distance from positive ideal solution and negative ideal solution is then calculated by using the below equation:

$$C_a = \frac{D_a^+}{D_a^+ + D_a^-}, \quad (5)$$

Table 5. Payoff matrix as obtained from the literature.

|   | C1   | C2    | C3    | C4  | C5    | C6    | C7    | C8    | C9    | C10   | C11   |
|---|------|-------|-------|-----|-------|-------|-------|-------|-------|-------|-------|
| A1 | 25   | 3.74  | 50000 | 50  | 10    | 2000  | 5     | 4     | 9     | 83.33 | 2     |
| A2 | 25   | 4.97  | 50000 | 50  | 10    | 1800  | 1.53  | 4     | 8     | 61.11 | 2     |
| A3 | 10   | 299   | 50000 | 50  | 10    | 1700  | 1.73  | 7     | 20    | 2     |
| A4 | 5    | 127999| 50000 | 85  | 350   | 500   | 0.75  | 5     | 3     | 3     |
| A5 | 10   | 72499 | 20000 | 94  | 350   | 328   | 0.2   | 4.5   | 3     | 0.6   | 3     |
| Max| Max  | Max   | Max   | Max | Min   | Min   | Min   | Min   | Max   | Min   | Max   |

Table 6. Normalized payoff matrix.

|   | C1      | C2       | C3       | C4      | C5      | C6      | C7      | C8      | C9      | C10     | C11     |
|---|---------|----------|----------|---------|---------|---------|---------|---------|---------|----------|---------|
| A1| 0.333   | 2.76E−06 | 0.227273 | 0.152   | 0.014   | 0.140   | 0.001   | 0.222   | 0.281   | 1.66     | 0.167   |
| A2| 0.333   | 3.68E−06 | 0.227273 | 0.152   | 0.014   | 0.126   | 0.0001  | 0.222   | 0.25    | 1.220    | 0.167   |
| A3| 0.133   | 0.000221 | 0.227273 | 0.152   | 0.014   | 0.119   | 0.0001  | 0.111   | 0.219   | 0.399    | 0.167   |
| A4| 0.067   | 0.946181 | 0.227273 | 0.258   | 0.480   | 0.035   | 7.5E−05 | 0.278   | 0.156   | 0.060    | 0.25    |
| A5| 0.133   | 0.053    | 0.091    | 0.286   | 0.480   | 0.052   | 0.022   | 0.231   | 0.094   | 0.004    | 0.25    |
| Max| Max     | Max      | Max      | Min     | Min     | Min     | Min     | Max     | Min     | Min      | Max     |
(2) Finally, the alternatives are ranked based on the $C_a$ values. The higher the $C_a$ value, the better the alternative and thus, it is the most viable desalination technology.

### 4.2 Results of TOPSIS evaluation

Each column of the normalized payoff matrix in Table 6 is multiplied with the weight of the corresponding criteria obtained from Table 4. For example, every element in column C1 in Table 6 is multiplied with 0.085. Similarly, every element in the column titled C2 is multiplied with 0.019 and likewise the weighted-normalized payoff matrix is obtained as given in Table 7.

In the next step, the nature of every criterion is converted to maximization multiplying a negative sign with those criterions whose nature was minimization. For each criterion, the positive ideal solution is the maximum value of the elements in the column and negative ideal solution is the minimum value of all the elements in that column. Likewise, 11 positive ideal and negative ideal values are obtained.

Table 8 is further used for the computation of the respective distances from positive and negative ideal solutions, i.e., $D^+_a$, $D^-_a$, and $C_a$ values using Equations (3)–(5) and is tabulated in Table 9.

It is observed from Table 9 that ranking pattern in the order of Alternatives A1–A5 is 5, 4, 3, 2 and 1. Thus, Alternative A5 is found to be the best due to its high $C_a$ value of 0.837. Evidently, according to the TOPSIS method, ED process is suitable for this community-based application over the other processes.

### 4.3 Evaluation using PROMETHEE-2: methodology

While TOPSIS was based on ranking according to the relative distance between each alternative, PROMETHEE-2 is an MCE technique of outranking nature. It is one among the five variations of PROMETHEE 1–5 [38–40]. PROMETHEE-2 is based on the preference function approach where preference function $P_j(a, b)$ depends on pairwise difference $d_j$ between the evaluations $f_j$ and $f_b$ of alternatives $a$ and $b$ for the criterion $j$. The preference function has been represented as $H(d_j)$ and the six types of criterion functions are available in the literature and are defined in Figure 4. Each criterion should be assigned with any of the preference functions depending on the judgments made by the decision maker. According to the PROMETHEE theories, for the appropriate selection of desalination technology from a set of alternatives, a multi-criterion preference index $\pi(a, b)$, a weighted average of the preference function must be defined as Equation (6)

$$\pi(a, b) = \frac{\sum_{j=1}^{11} w_j P_j(a, b)}{\sum_{j=1}^{11} w_j}$$

The outranking index, $\phi^+(a)$, of an alternative $a$ in the alternative set $N$, outranked index, $\phi^-(a)$, of an alternative $a$ in the alternative set $N$ and the net ranking, $\phi(a)$, of the alternative $a$ in the alternative set $N$ have been well defined in the literature and upon calculation, the ranking pattern of the alternative is

### Table 7: Weighted normal payoff matrix

|   | C1       | C2       | C3       | C4       | C5       | C6       | C7       | C8       | C9       | C10      | C11      |
|---|----------|----------|----------|----------|----------|----------|----------|----------|----------|----------|----------|
| A1| 0.029    | 5.34E-08 | 0.009    | 0.007    | 0.002    | 0.027    | 4.99E-05 | 0.003    | 0.007    | 0.441    | 0.007    |
| A2| 0.029    | 7.11E-08 | 0.009    | 0.007    | 0.002    | 0.025    | 1.53E-05 | 0.003    | 0.006    | 0.323    | 0.007    |
| A3| 0.011    | 4.28E-06 | 0.009    | 0.007    | 0.002    | 0.023    | 1.73E-05 | 0.001    | 0.005    | 0.106    | 0.007    |
| A4| 0.006    | 0.018    | 0.009    | 0.011    | 0.084    | 0.007    | 7.49E-06 | 0.003    | 0.004    | 0.016    | 0.001    |
| A5| 0.011    | 0.001    | 0.004    | 0.013    | 0.084    | 0.010    | 0.002    | 0.003    | 0.002    | 0.001    | 0.001    |

|   | Max      | Max      | Min      | Max      | Min      | Min      | Max      | Min      | Max      | Min      | Max      |

### Table 8: Weighted normalized payoff matrix, positive ideal and negative ideal values for each criterion.

|   | C1       | C2       | C3       | C4       | C5       | C6       | C7       | C8       | C9       | C10      | C11      |
|---|----------|----------|----------|----------|----------|----------|----------|----------|----------|----------|----------|
| A1| 0.029    | 5.34E-08 | 0.009    | 0.007    | -0.002   | -0.027   | -4.99E-05| 0.003    | -0.007   | -0.441   | 0.007    |
| A2| 0.029    | 7.11E-08 | 0.009    | 0.007    | -0.002   | -0.025   | -1.53E-05| 0.003    | -0.006   | -0.323   | 0.007    |
| A3| 0.011    | 4.28E-06 | 0.009    | 0.007    | -0.002   | -0.023   | -1.73E-05| 0.001    | -0.005   | -0.106   | 0.007    |
| A4| 0.006    | 0.018    | 0.009    | 0.011    | -0.084   | -0.007   | -7.49E-06| 0.003    | -0.004   | -0.016   | 0.010    |
| A5| 0.011    | 0.001    | 0.004    | 0.013    | -0.084   | -0.010   | 0.002    | 0.003    | -0.002   | -0.001   | 0.010    |

### Table 9: $D_a^+, D_a^-$ and $C_a$ values of alternatives.

|   | $D_a^+$ | $D_a^-$ | $C_a$ | Rank |
|---|---------|---------|-------|------|
| A1| 0.441   | 0.085   | 0.162 | 5    |
| A2| 0.324   | 0.145   | 0.310 | 4    |
| A3| 0.109   | 0.345   | 0.759 | 3    |
| A4| 0.086   | 0.426   | 0.831 | 2    |
| A5| 0.086   | 0.441   | 0.837 | 1    |
obtained as given by the below equations.

\[
\phi^+(a) = \frac{\sum_{A} \pi(a, b)}{N - 1}
\]

\[
\phi^-(a) = \frac{\sum_{A} \pi(b, a)}{N - 1}
\]

\[
\phi(a) = \phi^-(a) - \phi^+(a)
\]

4.4 Results of PROMETHEE-2 evaluation

The solution methodology of PROMETHEE-2 is divided into various steps for the computation of the ranking pattern of the various desalination alternatives. The analysis has been performed for all the criteria with maximization nature. Therefore, the payoff matrix in Table 5 is reproduced as Table 10, where all the criteria are converted to maximization nature by multiplying a negative sign with those criteria of minimization nature.

The parameters required for the PROMETHEE-2 method, such as the type of preference functions for each criterion, the thresholds for each criterion as defined in Figure 4, have been represented in Table 11. Since majority of the data collected during payoff matrix formation was obtained from the literature, to exclusively highlight even a small difference between the values in the payoff matrix, the usual preference function was used. However, for some criteria, data were obtained from surveys where opinion from the experts were tabulated and averaged. In order to account for the decision errors, quasi-criterion and level preference functions were selected so as to ignore very small difference between the values in the payoff matrix. Accordingly, the threshold values \( q_j \) for quasi-criterion were selected as 50% of the difference between maximum and

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**Figure 4.** Types of various criterion functions and relevant preference function values in PROMETHEE-2 [40].

**Table 10.** Transformed payoff matrix with all the criteria of maximization nature.

|   | C1 | C2 | C3 | C4 | C5 | C6 | C7 | C8 | C9 | C10 | C11 |
|---|----|----|----|----|----|----|----|----|----|-----|-----|
| A1 | 25 | 3.74 | 50000 | 50 | -10 | -2000 | -5 | 4 | -9 | -83.33 | 2 |
| A2 | 25 | 4.97 | 50000 | 50 | -10 | -1800 | -1.53 | 4 | -8 | -61.11 | 2 |
| A3 | 10 | 299 | 50000 | 50 | -10 | -1700 | -1.73 | 2 | -7 | -20 | 2 |
| A4 | 5 | 1279999 | 50000 | 85 | -350 | -500 | -0.75 | 5 | -5 | -3 | 3 |
| A5 | 10 | 72499 | 20000 | 94 | -350 | -328 | -0.2 | 4.5 | -3 | -0.6 | 3 |

**Table 11.** Parameters required for the PROMETHEE-2 method.

| Criteria | Preference function type | Parameters | Normalized weights |
|----------|--------------------------|------------|-------------------|
| C1       | Usual                    | N/A        | 0.085             |
| C2       | Usual                    | N/A        | 0.019             |
| C3       | Usual                    | N/A        | 0.039             |
| C4       | Usual                    | N/A        | 0.044             |
| C5       | Usual                    | N/A        | 0.176             |
| C6       | Usual                    | N/A        | 0.196             |
| C7       | Usual                    | N/A        | 0.1               |
| C8       | Quasi-criterion          | \( q_j = 1.25 \) | 0.012 |
| C9       | Usual                    | N/A        | 0.024             |
| C10      | Usual                    | N/A        | 0.265             |
| C11      | Level                    | \( q_j = 0.25, p_j = 0.5 \) | 0.040 |

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minimum value, and $q_j$ and $p_j$ values for level criterion were selected as 0.25 and 0.5 with similar assumptions.

After the preference function for each criterion is defined, pairwise difference ($d_{ij}$) between values of alternatives for each of the 11 criteria has been performed. For example, for Criterion C1, pairwise difference between alternatives A1 and A3 is 25. The corresponding preference function value $P_1(A_1, A_3)$ is 1 (as 15 = 1). Similarly, pairwise difference between A3 and A1 for Criterion C1 is 2 and the corresponding preference function $P_1(A_3, A_1)$ is 0 (as 2 = 0). Also, the pairwise difference between A1 and A1 is 0 as Alternative A1 is compared with itself. For Criterion C8 where the preference function type is assumed to be quasi-criterion, the preference function value is taken as 0 if the pairwise difference $d_{ij}/C_{20q_j}$ and if the pairwise difference $d_{ij}/C_{20p_j}$ then the preference function is taken as 1. For Criterion C11 with the level preference function, the preference function is taken as 0 if $d_{ij}/C_{20q_j}$, 0.5 if $q_j < d_{ij} < p_j$ and as 1 if $d_{ij} > p_j$.

Tables 12–22 represent the pairwise difference between alternatives for Criterion C1–C11 along with the preference function values for the respective criteria. Further, multi-criteria preference index, for all the pairwise alternatives, has been computed and is represented in Table 23.

The outranking index of $a$ in the alternatives set $N (\phi^+(a))$, the outranked index of $a$ in the alternative set $N (\phi^-(a))$ and the net ranking of $a$ in the alternative set $N (\phi(a))$ have been computed and the result is represented in Table 23.

It is observed from Table 24 that the ranking pattern in the order of Alternatives A1–A5 is 5, 4, 3, 2 and 1. Alternative A5 is
found to be the best due to its high $\phi$ value of 0.526. Thus, according to the PROMETHEE-2 method, ED process is suitable for this community-based application over the other available technologies.

4.5 Comparison of results

In the previous subsections, the viability evaluation is done through TOPSIS and PROMETHEE-2 techniques. The result obtained from these methods indicates that ED process is the most viable technology for the selected community-based application. Further, the ranking patterns obtained from both these processes indicate the usage of ED, RO, VC, MED and MSF in the decreasing order of priority. Evaluations using both the methods have resulted in the same ranking pattern; however, TOPSIS produced the results faster than PROMETHEE-2 as it has the ability to compare and analyze the complete data simultaneously. So, it can be concluded that when majority of the data for the calculation of viability is available in the literature and is quantitative in nature, TOPSIS can be used over PROMETHEE-2.

4.6 Procedure for other desalination applications

The viability evaluation was carried out for a community-based application with the small scale and brackish water desalination...
Eleven criteria affecting the desalination technology selection were identified and various methods of obtaining the desirable solution in MCE environment were mentioned.

TOPSIS and PROMETHEE-2 were chosen to be the suitable techniques for the desalination technology selection and the evaluations were performed.

TOPSIS and PROMETHEE-2 evaluation concluded that ED was found to be the most viable solution for a community-based application.

Slight modifications in the payoff matrix for different end-user applications would provide viable solutions to every such requirement.

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