Ranking of hydropower projects based on sustainability criteria in India using multicriteria decision making methods

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Article Info	ABSTRACT
	Assessment of hydropower projects with respect to sustainability criteria is a multidimensional and a complex issue that decision makers usually face during planning process. In hydropower projects, it is important to consider technical, environmental and social parameters instead of purely economic ones for sustainability assessment and decision making. Multi-criteria decision making (MCDM) methods offer a practical approach to a problem having conflicting criteria. The flexibility to consider several criteria and objectives simultaneously made MCDM methods well accepted in the field of energy planning. This paper aims for applicability of MCDM methods which will facilitate the decision makers to select the most sustainable hydropower projects by making real and logical choices based on various sustainability criteria. For comprehensively rank hydropower projects of Indian region based on sustainability criteria four MCDM methods are applied i.e., analytic hierarchy process (AHP), technique for order of preference by similarity to ideal solution (TOPSIS), preference ranking organization method for enrichment evaluations (PROMETHEE II) and elimination and choice translating reality (ELECTRE III). To ensure better decision making the eight criteria selected are compatible to the sustainable development of hydropower projects.

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1. INTRODUCTION

Hydropower is recognized as a mature technology for electricity generation and is globally contributing maximum towards the generation of all the renewable resources. Hydropower has storage reservoir, which helps to meets the peak load demand and thus stabilize the overall electrical grid [1]. Hydropower apart from generating low-cost electricity provides water supply, flood control, drought management, recreation, irrigation, and job creation [2], [3]. Regardless of these several advantages, the development of hydropower used to be highly controversial on account of it's social and environmental impacts in terms of loss of biodiversity, destroying of the ecosystem, greenhouse gas (GHG) emissions, submergence of large land area, displacement and resettlement of population [4]. Therefore, in the field of hydropower development sustainability has become an important concern.

Previously technical and economic parameters were the main criteria to analyze the hydropower projects which mainly focused on electricity generation [5]. Later environmental and social aspects were also considered as significant criteria for sustainability assessment of hydropower projects [6]. Hence it becomes

necessary to consider all i.e., technical, economic, social and environmental criteria for assessing the sustainability of hydropower project. However, these criteria are contradicting as it is not possible to design an economical, high installed capacity hydropower project with negligible environmental and social impacts, further some impacts are bound to happen. Therefore, to tackle the hydropower system with a perception of sustainability as a complex problem, multi-criteria decision making (MCDM) methods serve as a quite realistic approach which includes, among others, some conflicting criteria [7].

There are several MCDM methods which are widely applied to the application of energy planning, sustainability assessment and ranking of renewable energy projects such as hydropower, wind, solar, geothermal, etc. For example, analytic hierarchy process (AHP) is applied in [8] to study the potential to develop hydropower projects. To assisting energy planning [9] also used AHP to evaluate and rank the hydropower projects specifically to the hydropower plants constructions in the mountainous area of Italy and [10] used AHP to determine the most suitable site for a wind observation station. Preference ranking organization method for enrichment evaluations (PROMETHEE) method with fuzzy input data has been used to assessed and ranked alternative energy exploitation schemes of a low-temperature geothermal field using [11]. Moreover [12] developed the framework using the PROMETHEE method to arrive for group consent on renewable energy projects, which was then applied to a geothermal reservoir project on the island of Chios and [13] applied PROMETHEE for assessing the sustainability of renewable energy technologies in Scotland. Elimination and choice translating reality (ELECTRE) method had been applied by [14] and [15] in the application of renewable energy planning. Technique for order of preference by similarity to ideal solution (TOPSIS) under fuzzy environment has been used for evaluating sustainability and ranking of renewable energy technologies [16]-[18]. The MCDM methods help in better decision making by efficiently considering numerous criteria with conflicting nature. Depending on the objective of planning and application area, each MCDM method has its own strength and weakness [19]. Hence no single method can be categorized as best or worst.

The present study demonstrates the application of most often used MCDM methods namely AHP, TOPSIS, PROMETHEE II, and ELECTRE III on a practical example for ranking of major hydropower projects of India based on eight sustainability criteria. The AHP method is used to evaluate the weights of the criteria used for assessing the sustainability of hydropower projects. The various criteria considered for ranking of hydropower projects in this study are based on techno-economic, economic, environmental and social.

2. METHODOLOGY
2.1. Weights calculation by AHP method

The AHP introduced by Saaty is the most widely accepted decision support tool for complicated decision problems [20]. AHP uses a multi-level hierarchical formation of objectives, criteria, sub-criteria, and alternatives.

The following steps are involved in the AHP method [21].

(i)   Construct a pairwise comparisons matrix of the criteria involved in the decision using a numerical scale for comparison used in [20]. Let C_j ($j=1, 2, . . ., n$) represents the jth criteria. B presents the (n x n) pairwise comparison matrix, where b_{ij} ($i, j=1, 2, . . ., n$) represents the relative importance of criteria i with respect to criteria j. A criterion compared with itself is always assigned the value 1.

$$B = \begin{bmatrix} 1 & b_{12} & \ldots & b_{1n} \\ b_{21} & 1 & \ldots & b_{2n} \\ \ldots & \ldots & \ldots & \ldots \\ b_{n1} & b_{n2} & \ldots & 1 \end{bmatrix} \quad b_{ji} = {}^1\!/_{b_{ij}}, b_{ij} \neq 0 \tag{1}$$

(ii) The relative normalized weight (Wi) is calculated by calculating the value of the geometric mean (GM_i) of its row.

$$GM_i = \{b_{i1} \times b_{i2} \times b_{i3} \times \ldots \times b_{ij}\}^{1/n} \tag{2}$$

$$W_i = \frac{GM_i}{\Sigma_{j=1}^{j=n} GM_i} \tag{3}$$

(iii) Determine the matrix Y such that $Y = B \times W$, where

$$W = [W_1, W_2, W_3, \ldots, Wn]^T \tag{4}$$

$$Y = B * W = \begin{bmatrix} 1 & b_{12} & \ldots & b_{1n} \\ b_{21} & 1 & \ldots & b_{2n} \\ \ldots & \ldots & \ldots & \ldots \\ b_{n1} & b_{n2} & \ldots & 1 \end{bmatrix} \begin{bmatrix} W_1 \\ W_2 \\ \ldots \\ W_n \end{bmatrix} = \begin{bmatrix} C_1 \\ C_2 \\ \ldots \\ C_n \end{bmatrix} \tag{5}$$

(iv) The consistency values (CV) calculated for the group of alternatives is given by (6).

$$CV_i = \frac{c_i}{w_i} \tag{6}$$

(v) The value of the maximum eigenvalue λmax is then calculated which is the average of the consistency values.

(vi) The value of the consistency index (CI)=(λmax-n)/(n-1) is calculated wherein 'n' denotes the total number of criteria. The consistency of the pairwise comparison denotes the quality of the results of the AHP.

(vii) The value of the random index (RI) is selected using Table 1 for the number of criteria.

(viii) The value of consistency ratio (CR)=CI/RI is then calculated. The value 0.1 is the accepted upper limit for CR. If the value of CR exceeds the value 0.1, then complete evaluation procedure has to be repeated to improve consistency as the value of CR denotes the consistency of decision makers as well as of overall hierarchy.

Table 1. Random index (*RI*) values [21]

Criteria	RI	Criteria	RI
3	0.52	7	1.35
4	0.89	8	1.4
5	1.11	9	1.45
6	1.25	10	1.49

2.2. Methods for ranking of alternatives
2.2.1. The TOPSIS method

The TOPSIS method, developed by Hwang and Yoon [22], is based on the principle that the best alternative is closest to the positive ideal solution and farthest from the negative ideal solution [23], [24]. The formal TOPSIS method comprises of the following steps:

(i) A decision matrix has to be established for the ranking wherein columns represent criteria (C_1, C_2, C_3, ..., C_n), (j=1, 2, ..., n) while rows represent alternatives (A_1, A_2, A_3, ... A_m), (i=1, 2, ..., m).

$$\begin{array}{cccc} & C_1 & C_2 & \ldots & C_n \\ & (W_1) & (W_2) & \ldots & (W_n) \\ \begin{matrix} A_1 \\ A_2 \\ A_m \end{matrix} & \begin{bmatrix} X_{11} & X_{12} & \ldots & X_{1n} \\ X_{21} & X_{22} & \ldots & X_{2n} \\ X_{m1} & Xm2 & & Xmn \end{bmatrix} \end{array} \tag{7}$$

An element X_{ij} of the matrix indicates the performance rating of the ith alternative A_i, with respect to the jth criteria C_j, as shown in (7).

(ii) The normalized decision matrix rij of Xij is calculated as defined in (8)

$$r_{ij} = \frac{X_{ij}}{\sqrt{\Sigma_{i=1}^{i=m} X_{ij}^2}} \quad i = 1,2,\ldots,m; \; j = 1,2,\ldots,n \tag{8}$$

(iii) Weighted normalized decision matrix v_{ij} is calculated by multiplying the normalized decision matrix by its corresponding weights.

$$v_{ij} = W_j * r_{ij} \tag{9}$$

(iv) The values of positive ideal (best) (V+) and negative ideal (worst) solutions (V-) is then calculated using (10) and (11).

$$V+=\left\{\left(\sum_i^{max} v_{ij} \,/\, j \in J\right), \left(\sum_i^{min} v_{ij} \,/\, j \in J'\right) \,/\, i = 1, 2, \dots, m\right\}$$
$$=\left\{v_1^+, v_2^+, v_3^+, \dots, v_n^+\right\} \tag{10}$$

$$V^- = \left\{\left(\sum_i^{min} v_{ij} \,/\, j \in J\right), \left(\sum_i^{max} v_{ij} \,/\, j \in J'\right) \,/\, i = 1, 2, \dots, m\right\}$$
$$=\left\{v_1^-, v_2^-, v_3^-, \dots, v_n^-\right\} \tag{11}$$

where $J=(j=1, 2, \dots, n)/j$ is set of beneficial criteria and $J'=(j=1, 2, \dots, n)/j$ is set of nonbeneficial criteria.

(v) The separation between alternatives can be calculated by the n-dimensional Euclidean distance. The separation of each alternative from the positive ideal solution is given as (12).

$$S_i^+ = \sqrt{\sum_{j=1}^n v_{ij} - v_j^{+2}} \quad i=1, 2, \dots, m \tag{12}$$

Similarly, the separation from the negative ideal solution is as (13).

$$S_i^- = \sqrt{\sum_{j=1}^n v_{ij} - v_j^{-2}} \quad i=1, 2, \dots, m \tag{13}$$

(vi) The relative closeness of the alternative Aij from the ideal solution, is calculated as (14).

$$R_i = \frac{s_i^-}{s_i^+ + s_i^-} \ (14) \tag{14}$$

(vii) Finally, the alternatives are ranked in the descending order according to the value of R_i.

2.2.2. The PROMETHEE method

The PROMETHEE is an effective MCDM tool and popular outranking method [25]. In PROMETHEE method a finite 'm' number of alternatives A=[A1, A2, …, Am] are evaluated for a finite 'n' number of evaluation criteria C=[C1, C2, …, Cn]. PROMETHEE has proved to be an excellent tool for ranking considering multiple and complex criteria when dealing with the finite number of alternatives [26], [27]. The versions available of PROMETHEE are PROMETHEE I, PROMETHEE II, PROMETHEE III, PROMETHEE IV and PROMETHEE VI. Based on the user-friendly approach and mathematical property, each PROMETHEE method can be regarded as a convenient tool for decision making [28].

In present study PROMETHEE II is applied as it is the most commonly used version which allows decision maker to find a full ranked vector of alternatives and it is well fitted to the case study undertaken. In this method, alternatives are evaluated by pairwise comparison on a particular criterion and based on the deviation the preference is assigned for the best alternative by a decision maker. The preference assigned is the value between '0-1' that is according to the selected preference function. The six preference functions had been proposed by [25], which are namely, usual criterion (Type I), quasi criterion (Type II), criterion with linear preference (Type III), level criterion (Type IV), criterion with linear preference and indifference area (Type V), and Gaussian criterion (Type VI) [29]. The introduction of an indifference threshold in decision making will decide the selection of Type I or IV; and Type III or V preference function.

The preference of alternative A1 over alternative A2 for a particular criterion C_j can be determined by means of a preference function $P_j(A_1, A_2)$ such that $0 \le P_j(A_1, A_2) \ge 1$, which expresses the preference as a function of the deviation $d_j(A_1, A_2)$ between A1 and A2 on that particular criterion:

$$P_j(A_1, A_2) = F_j\left[d_j(A_1, A_2)\right] = F_j\left[C_j(A_1) - C_j(A_2)\right] \tag{15}$$

where F_j represents the function of the deviation. Figure 1 presents the linear preference function, which requires to define the parameters q_j i.e., indifference threshold and p_j i.e., outright preference threshold for each criterion considered. The parameter q_j is defined as the largest deviation, which is considered negligible by the decision maker. The parameter p_j is defined as the smallest deviation, which is considered sufficient to generate a full preference [25]. The index of preference $\prod(A_1, A_2)$ of alternative A_1 being preferred over alternative A_2 is given by (16).

$$\prod(A_1, A_2) = \frac{\sum_{j=1}^{n} P_j(A_1, A_2) W_j}{\sum_{j=1}^{n} W_j} \tag{16}$$

$\prod(A_1, A_2)$ is a number between 0 and 1 that represents the degree to which A_1 is preferred over A_2, while $\prod(A_2, A_1)$ represents the preference of A_2 over A_1. W_j is the weight assigned to criteria j. To rank one alternative against all the other alternatives, the positive and negative outranking flows given by (17) and (18) are calculated and finally, net outranking flow is calculated by (23).

$$\emptyset^+(A_1) = \frac{1}{(n-1)} \sum_{B \in A} \prod(A_1, B) \tag{17}$$

$$\emptyset^-(A_1) = \frac{1}{(n-1)} \sum_{B \in A} \prod(B, A_1) \tag{18}$$

$$\emptyset(A_1) = \emptyset^+(A_1) - \emptyset^-(A_1) \tag{19}$$

The positive outranking flow $\emptyset^+(A_1)$ in (17) indicates how the alternative A_1 is outranking all the others, while the negative outranking flow $\emptyset^-(A_1)$ in (18) indicates how the alternative A_1 is outranked by all the others. Higher the $\emptyset^+(A_1)$ and lower the $\emptyset^-(A_1)$ indicates, A_1 is better in comparison to the other alternatives. The value of the net outranking flow ($\emptyset$) calculated for each alternative using (19) is used to rank the alternatives. The highest rank will be assigned to the alternative with the greatest value of $\emptyset$.
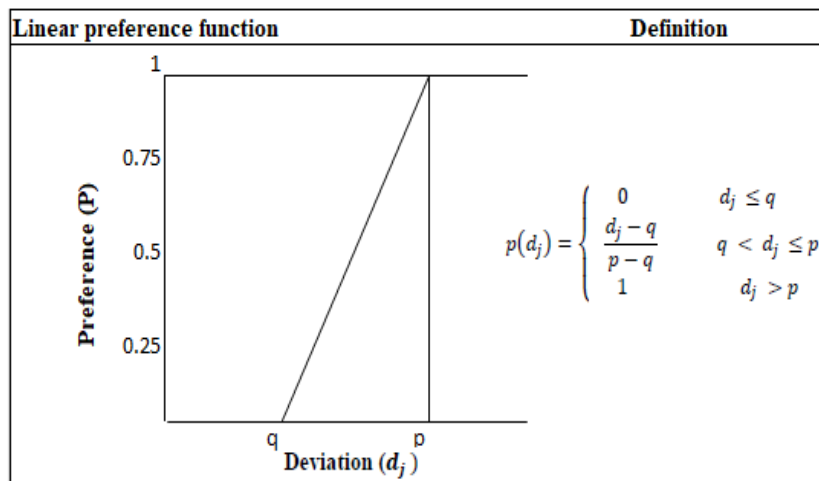

Figure 1. Linear preference function

2.2.3. The ELECTRE method.

The ELECTRE method was first proposed by Roy [30] in 1991. The method is based upon outranking concept whereby an alternative a_1 outranks another alternative a_2 with enough fact exists to declare that a_1 is as good as a_2 and good reasons to reject such facts do not exist. The available versions of ELECTRE are: ELECTRE I, II, III, IV, IS and TRI [31]. The present study ELECTRE III is selected for ranking the alternatives as this method provides an advantage of the direct participation of decision maker and a possibility to analyze both qualitative and quantitative criteria [32]-[34].

Let alternatives A=(a_1, a_2, ..., a_m) are assess for a finite n number of criteria (g_1, g_2, ..., g_n); $g_j(a_j)$ represents the performance of the alternative a $\in$ A for the criteria g_j (j=1, 2, ..., n). The ranking procedure of the ELECTRE III model requires to define the threshold function. Let the indifference and threshold for the jth criteria are represented q_j and p_j respectively [35].
If $g(a_1) \geq g(a_2)$, then,

$$g(a_1) > g(a_2) + p \iff a_1 P a_2 \tag{20}$$

$$g(a_2) + q < g(a_1) < p \iff a_1 Q a_2 \tag{21}$$

$$g(a_2) < g(a_1) < g(a_2) + q \Leftrightarrow a_1 I a_2 \tag{22}$$

where P denotes a strong preference, Q denotes a weak preference, I denote an indifference and $g(a_1)$ is the criteria value of the alternative a_1.

The ELECTRE III ranking calculations involve following steps:

(i)   The concordance index $C(a_1, a_2)$ is computed for each pair of alternatives:

$$C_j(a_1, a_2) = \frac{\sum_{j=1}^n w_j \, C_j(a_1, a_2)}{\sum_{j=1}^n w_j} \tag{23}$$

where $C_j\left(a_1, a_{2,}\right)$ is the outranking degree of the alternative a_1 and $a_{2,}$ under criteria j

$$C_j(a_1, a_2) = \begin{cases} 0 \ if \ g_j(a_2) - g_j(a_1) \geq p_j \\ 1 \ if \ g_j(a_2) - g_j(a_1) \leq q_j \\ p_j + g_j(a_1) - g_j(a_2) \Big/ p_j - q_j \end{cases} \tag{24}$$

Thus $0 \leq C_j(a_1, a_2) \leq 1$.

The relation between $q_j, p_j \ and \ v_j$ is as (25).

$$q_j < p_j < v_j \tag{25}$$

The veto threshold (v) allows the possibility of $a_1 S a_2$ i.e outranking to be refused totally if, for anyone criteria j, $g_j(a_2) > g_j(a_1) + v_j$.

(ii)   The discordance index $d(a_1, a_2)$ for each criterion is then defined as (26).

$$d_j(a_1, a_2) = \begin{cases} 0 \ if \ g_j(a_2) - g_j(a_1) \leq p_j \\ 1 \ if \ f g_j(a_2) - g_j(a_1) \geq v_j \\ g_j(a_2) - g_j(a_1) - p_j \Big/ v_j - p_j \end{cases} \tag{26}$$

Thus $0 \leq d_j(a_1, a_2) \leq 1$

(iii)   Finally, the degree of outranking is defined by (27).

$$S(a_1, a_2) = \begin{cases} C(a_1, a_2) \ if \ d_j(a_1, a_2) \leq C(a_1, a_2) \ \forall j \, \epsilon \, J \\ C(a_1, a_2) \times \prod_{j \epsilon J(a_1, a_2)} \frac{1 - d_j(a_1, a_2)}{1 - C(a_1, a_2)} \ otherwise \end{cases} \tag{27}$$

Where $J(a_1, a_2)$ is the set of the criteria for which $d_j(a_1, a_2) > C(a_1, a_2)$.

(iv)   For complete ranking in ELECTRE III method, the present study used the procedure adopted in [36].
          This procedure requires to calculate the concordance credibility degree, the discordance credibility degree, and the net credibility degree:

(a)   The concordance credibility degree is defined as (28).

$$\emptyset^+(a_i) = \sum_{b_i \, \epsilon A} S(a_i, b_i) \, , \forall a_i \, \epsilon \, A \tag{28}$$

The concordance credibility degree measures the outranking character of a_i i.e. how a_i dominates all other alternatives of A.

(b)   The discordance credibility degree is defined as (29).

$$\emptyset^-(a_1) = \sum_{b_i \, \epsilon A} S(b_i, a_i) \ \ \forall a_i \, \epsilon \, A \tag{29}$$

(c)   The net credibility degree is then calculated as (30).

$$\emptyset(a_1) = \emptyset^+(a_1) - \emptyset^-(a_1) \tag{30}$$

The high value of the net credibility degree represents higher preference of the alternative A_i over other alternatives. Hence the ranking of alternatives is done based on the value of the net credibility degree.

3.   SUSTAINABILITY ASSESSMENT AND RANKING OF ALTERNATIVES
3.1. Selection of alternatives
The first step in MCDM is the selection of the alternatives. The 14 major hydropower projects from various regions of India are carefully selected as alternatives with a focus on projects having installed capacity more than 200MW, displacement or resettlement of more than 4000 people and having a large reservoir to make the problem more objective. Table 2 presents the list of selected hydropower projects.

Table 2. List of selected hydropower projects

Alternatives	Hydro power project	State	Installed capacity (MW)
A_1	Balimela	Odisha	510
A_2	Bhakra	Himachal Pradesh	1325
A_3	Hirakud	Odisha	347
A_4	Indira Sagar	Madhya Pradesh	1000
A_5	Pong	Himachal Pradesh	396
A_6	Rengali	Odisha	250
A_7	Rihand	Uttar Pradesh	300
A_8	Sardar Sarovar	Gujrat	1450
A_9	Sharavathi	Karnataka	1035
A_{10}	Srisailam	Telangana	770
A_{11}	Tehri	Uttarakhand	1000
A_{12}	Ukai	Gujrat	300
A_{13}	Upper Indravati	Odisha	600
A_{14}	Upper Kolab	Odisha	320

3.2. Selection of evaluation criteria
The second step is very critical under MCDM approach i.e. identification and selection of criteria to compare the alternatives with respect to a particular perspective. For sustainability evaluation of renewable energy generation technologies, ranges of criteria should be considered [37]. The accessible information in terms of quantitative and qualitative data of alternatives will decide the selection of number of criteria. The criteria selected in the present study for ranking of hydropower projects based on sustainability are, installed capacity, average electricity generation, capacity factor, cost of generation, land use, displacement of people, safety and social benefits. Table 3 presents the summary of selected criteria, preference criteria to be maximum or minimum and studies undertaken which supports the selection of these criteria. The study takes into account all four types of criteria which are well known pillars of sustainability i.e., techno-economic, economic, environmental and social as follows:

3.2.1. Techno-economic
The criteria selected in this type are installed capacity, annual energy production, and capacity factor. Mostly in the available literature, these criteria are merged with the economic criteria [37], [38], whereas some have considered them in technical or generation aspects [8], [13]. Therefore, in the present study, these selected criteria have been considered as techno-economic criteria.
− Installed capacity: In the present study installed capacity is a direct indication of the potential to generate the power.
− Electricity generation per year: Annual energy production directly improves the economy of power projects.
− Capacity factor: The capacity factor is defined as the ratio of the total actual energy generated over a definite period, to the energy that would have been generated if the power plant had operated continuously at the maximum rating. Capacity factor shows the power project capacity to produce energy without any kind of defect or break down.

3.2.2. Economic

This criterion represents the cost and profit of the hydropower projects with respect to long term success. Cost of generation: It is a major criterion regards to the economic sustainability of the project. An economically sound project because of its low generation cost offers good investment opportunities [6].

3.2.3. Environmental

This criterion represents the project's environmental affinity with the surrounding region and ecology. Land use: The land use in the form of the reservoir may destroy the ecosystem. It results in greenhouse gas emissions, soil erosion, silt deposition, obstruction to fish migration. The land coverage in the form flooding area of dam cause loss of farming plots, loss of spiritual places and increase infectious disease [39].

3.2.4. Social

The social criteria indicate the life of local communities affected or benefited by the construction of hydropower projects. Public perception plays an important role in the deployment of hydropower projects [40].

− Displacement and resettlement: The main social impact of the construction of large hydropower dam reservoirs are the displacement and resettlement of affected communities. This forced displacement and the resettling process do not guarantee the same life that existed before. Hence from a sustainability point of view resettlement or displacement should be minimum.

− Safety: As far as the safety of hydropower projects is concerned, the failure of dams caused by earthquakes still remains a serious threat as they are capable to completely break the dam with the energy released from the event [41]. Based on the historical seismic activity, the regions of India have been classified into four seismic zones by the Bureau of Indian Standards. These are zone II (low-intensity zone), zone III (moderate intensity zone), zone IV (severe intensity zone) and zone V (very severe intensity zone). Based on the zone on which selected dams fall, safety is marked in the scale of (1-4). The dams which fall on zone II have been scaled 4 i.e safer compared to other zones. Similarly scaling for zone III is 3, zone IV is 2 and zone V is 1 respectively.

− Social benefits: The benefits such as irrigation, flood control, recreation along with generation are also the major criteria from a sustainability point of view [37], [39]. The selected hydropower projects were scaled on (1-4) based on the benefits they are providing. For example, the hydropower projects which serve the propose of only power generation were scaled as 1 and hydropower projects which serve the purpose of generation, irrigation, flood control, and recreation was scaled as 4 respectively.

Table 3. Summary of selected criteria

Criterion	Type	Unit	Preference Criterion	Reference study
Installed capacity (C_1)	Techno-economic	MW	Maximum	[8], [38]
Electricity generation per year (C_2)	Techno-economic	MU/year	Maximum	[8], [13]
Capacity factor (C_3)	Techno-economic	percentage	Maximum	[42]
Cost of generation (C_4)	Economic	Paisa/kWh	Minimum	[8], [37]
Land use (C_5)	Environmental	hector	Minimum	[9], [13], [37]
Displacement (C_6)	Social	Persons	Minimum	[8], [9], [37]
Safety (C_7)	Social	Qualitative (1-4)	Maximum	[8]
Social benefits (C_8)	Social	Qualitative (1-4)	Maximum	[2], [37]

3.3. Weights calculation of criteria by AHP

The criteria weights by AHP methods are calculated per the steps mentioned in section 2.1. Table 4 presents the value of weights. Using steps vi-viii mentioned in section 2.1, the value of *CR* obtained is 0.0578 which is acceptable under limit CR ≤ 0.1. Therefore, there exist the consistency in weights and can be used for the sustainability assessment.

$$
B = \begin{bmatrix}
1 & 1/5 & 1/5 & 1/7 & 1/3 & 1/3 & 3 & 1/3 \\
5 & 1 & 1 & 1 & 3 & 3 & 5 & 3 \\
5 & 1 & 1 & 1/3 & 3 & 3 & 5 & 3 \\
3 & 1/3 & 1/3 & 1/5 & 1 & 1 & 3 & 3 \\
3 & 1/3 & 1/3 & 1/5 & 1 & 1 & 3 & 3 \\
7 & 1 & 3 & 1 & 5 & 5 & 5 & 7 \\
1/3 & 1/5 & 1/5 & 1/5 & 1/3 & 1/3 & 1 & 1/3 \\
3 & 1/3 & 1/3 & 1/7 & 1/3 & 1/3 & 3 & 1
\end{bmatrix}
$$

Table 4. Criteria weights calculated using AHP

Criterion	GM	Criterion weight (W)	X=B. W	CV
C_1	0.3984	0.0368	0.3236	8.7925
C_2	2.2577	0.2086	1.7208	8.25
C_3	1.968	0.1818	1.5107	8.3087
C_4	3.4122	0.3152	2.7248	8.6436
C_5	0.9381	0.0867	0.7296	8.4176
C_6	0.9381	0.0867	0.7296	8.4176
C_7	0.3157	0.0292	0.2587	8.8694
C_8	0.5958	0.055	0.486	8.8289
		λ_{max}=Avg (CV) 8.5660		

3.4. Sustainability ranking of hydropower projects

The values of the selected criterion for hydropower projects (alternatives) are presented in Table 5 along with weights calculated using AHP as shown in Table 4. Table 5 will be the input decision matrix to all the methods employed for sustainability ranking of hydropower projects wherein C_1, C_2, C_3, C_7, C_8 are beneficial criteria (larger the better) and C_4, C_5, C_6 are cost criteria (smaller the better). The ranking of hydropower projects is based on the following selected methods:

Table 5. Values for selected criterion for each selected alternative [a]

	C_1	C_2	C_3	C_4	C_5	C_6	C_7	C_8
A_1	510	1240.93	28	88.22	17496	10000	2	4
A_2	1325	6117	53	33.07	16600	36000	3	2
A_3	347	564.49	19	127.64	74300	11000	2	3
A_4	1000	2542.72	29	243.86	90820	80500	2	3
A_5	396	1315.48	38	23.62	29000	150000	2	2
A_6	250	710.1	32	108.09	414500	80000	3	4
A_7	300	572.11	22	55	46900	60000	2	3
A_8	1450	2909	23	205	37590	320000	2	3
A_9	1035	5147.47	57	27.69	5921	12500	1	3
A_{10}	770	1141.04	17	398.2	60629	100000	2	4
A_{11}	1000	2967.13	34	587	4200	100000	2	2
A_{12}	300	708.73	27	33	60000	80000	3	3
A_{13}	600	2597.23	49	80.42	11000	26505	2	4
A_{14}	320	702.7	25	49.84	11350	15895	2	4
Weight (Wj)	0.0368	0.2086	0.1818	0.3152	0.0867	0.0867	0.0292	0.055

[a] Values of criteria (C_1, C_2, C_4, C_5, C_6) for selected hydropower projects is taken from [43], [44] and values for criteria (C_3, C_7, C_8) is calculated as discussed in section 3.2 using data from the website of specific hydropower projects.

3.4.1. The TOPSIS method

As per the steps elaborated in section 2.2.1, Table 5 is the input decision matrix for TOPSIS analysis. The normalized decision matrix is calculated using (8). Further the rank of alternatives is obtained by following the steps iii–vi as mentioned in section 2.2.1. Table 6 presents the results obtained by TOPSIS method. Lastly, according to the value of Ri, the ranking is given to alternatives as A_2–A_9–A_{13}–A_5–A_1–A_{14}–A_{12}–A_7–A_3–A_8–A_4–A_6–A_{10}–A_{11}. Hence it can be concluded that hydropower project A_2 i.e. Bhakra and A_9 i.e. Sharavathi are most sustainable hydropower projects under the given eight criteria.

Table 6. TOPSIS method results

	C_1	C_2	C_3	C_4	C_5	C_6	C_7	C_8	S_i^+	S_i^-	R_i
A_1	0.0063	0.0257	0.0394	0.0343	0.0034	0.0021	0.0071	0.0182	0.1126	0.2201	0.6616
A_2	0.0165	0.1269	0.0745	0.0129	0.0032	0.0076	0.0106	0.0091	0.0129	0.2685	0.9543
A_3	0.0043	0.0117	0.0267	0.0497	0.0145	0.0023	0.0071	0.0137	0.1348	0.2015	0.5993
A_4	0.0124	0.0527	0.0408	0.0949	0.0177	0.0169	0.0071	0.0137	0.1223	0.1626	0.5707
A_5	0.0049	0.0273	0.0534	0.0092	0.0056	0.0315	0.0071	0.0091	0.1086	0.2369	0.6857
A_6	0.0031	0.0147	0.0450	0.0421	0.0807	0.0168	0.0106	0.0182	0.1474	0.1946	0.5691
A_7	0.0037	0.0119	0.0309	0.0214	0.0091	0.0126	0.0071	0.0137	0.1273	0.2260	0.6396
A_8	0.0180	0.0603	0.0323	0.0798	0.0073	0.0672	0.0071	0.0137	0.1265	0.1738	0.5787
A_9	0.0129	0.1068	0.0801	0.0108	0.0012	0.0026	0.0035	0.0137	0.0225	0.2650	0.9219
A_{10}	0.0096	0.0237	0.0239	0.1550	0.0118	0.0210	0.0071	0.0182	0.1888	0.1121	0.3726
A_{11}	0.0124	0.0616	0.0478	0.2285	0.0008	0.0210	0.0071	0.0091	0.2321	0.1080	0.3176
A_{12}	0.0037	0.0147	0.0380	0.0128	0.0117	0.0168	0.0106	0.0137	0.1222	0.2326	0.6555
A_{13}	0.0075	0.0539	0.0689	0.0313	0.0021	0.0056	0.0071	0.0182	0.0780	0.2297	0.7465
A_{14}	0.0040	0.0146	0.0351	0.0194	0.0022	0.0033	0.0071	0.0182	0.1223	0.2328	0.6556
V_j^+	0.0180	0.1269	0.0801	0.2285	0.0807	0.0672	0.0106	0.0182			
V_j^-	0.0031	0.0117	0.0239	0.0092	0.0008	0.0021	0.0035	0.0091			

3.4.2. The PROMETHEE method

As per the methodology described in section 2.2.3, Table 7 presents the selected preference function and the values of thresholds i.e., q and p for each criterion. The values of outranking flows i.e., $\emptyset^+, \emptyset^-$ and $\emptyset$ is calculated using (17), (18) and (19) and alternatives are ranked according to the value of $\emptyset$ as presented in Table 8.

Table 7. Selected preference function and threshold parameters

Criterion	Preference function	Threshold q	Threshold p
C_1	Linear	100	200
C_2	Linear	300	2000
C_3	Linear	5	15
C_4	Linear	20	100
C_5	Linear	2000	10000
C_6	Linear	2000	10000
C_7	Usual	n/a	n/a
C_8	Usual	n/a	n/a

Table 8. Outranking flow and ranking pattern of alternatives

Alternative	$\emptyset^+$	$\emptyset^-$	$\emptyset$	Rank
A_1	0.6933	0.0628	0.6306	5
A_2	0.6739	0.0992	0.5747	2
A_3	0.5401	0.1357	0.4044	13
A_4	0.307	0.2075	0.0995	12
A_5	0.3092	0.2292	0.08	6
A_6	0.3332	0.305	0.0282	9
A_7	0.2512	0.3036	-0.0525	8
A_8	0.2236	0.3333	-0.1097	11
A_9	0.2261	0.3958	-0.1697	1
A_{10}	0.2947	0.5149	-0.2202	14
A_{11}	0.2646	0.4982	-0.2336	10
A_{12}	0.2469	0.4899	-0.243	7
A_{13}	0.1875	0.4699	-0.2824	3
A_{14}	0.1287	0.6349	-0.5062	4

3.4.3. The ELECTRE method

The ranking procedure of the ELECTRE III method requires to define the q, p and v thresholds for the criteria. The selected values of thresholds for criteria are presented in Table 9. Table 10 presents the $S(a_1, a_2)$, concordance credibility ($\emptyset^+$), discordance credibility ($\emptyset^-$) and net credibility ($\emptyset$) calculated using (28), (29) and (30) and finally the ranking to the alternatives is given according to the value of ($\emptyset$).

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Table 9. Selected values of thresholds for criteria

Criterion	q	p	v
C_1	100	200	400
C_2	300	2000	4000
C_3	5	15	30
C_4	20	100	200
C_5	2000	10000	20000
C_6	2000	10000	20000
C_7	0	1	2
C_8	0	1	2

Table 10. The degree of outranking and ranking of alternatives

	A_1	A_2	A_3	A_4	A_5	A_6	A_7	A_8	A_9	A_{10}	A_{11}	A_{12}	A_{13}	A_{14}	$Ø^+$
A_1	1	0	1	0	0.7334	0.9708	0.9479	0	0	0.9632	0	0.832	0.6399	0.8827	7.97
A_2	0	1	0	0.945	1	0	0.945	0.9385	0	0	0.9133	0.945	0	0	6.68
A_3	0	0	1	0	0	0.7404	0	0	0	0	0	0.5355	0	0	2.31
A_4	0	0	0	1	0	0.6006	0	0	0	0	0	0	0	0	1.60
A_5	0	0	0	0	1	0	0	0	0	0	0	0	0	0	1.00
A_6	0	0	0	0	0	1	0	0	0	0	0	0	0	0	1.00
A_7	0	0	0	0	0.3611	0.8249	1	0	0	0	0	0.9629	0	0	3.15
A_8	0	0	0	0	0	0	0	1	0	0	0	0	0	0	1.00
A_9	0.9104	0	0.9708	0.9708	0.9708	0	0.9708	0	1	0.9158	0.9708	0	0.9158	0.9158	9.51
A_{10}	0	0	0	0.0139	0	0	0	0	0	1	0	0	0	0	1.01
A_{11}	0	0	0	0	0	0	0	0	0	0	1	0	0	0	1.00
A_{12}	0	0	0	0	0	0	0	0	0	0	0	1	0	0	1.95
A_{13}	0.9133	0	0.9133	0	0.855	0.9708	0.9786	0	0	0.9742	0	0.8628	1	0.8716	8.34
A_{14}	0.8954	0	0.9686	0	0.7917	0.9344	1	0	0	0	0	0.9708	0.5656	1	7.13
$Ø^-$	3.72	1.00	4.85	4.85	5.71	7.02	5.84	1.94	1.00	3.85	2.88	6.11	3.12	3.67	
$Ø$	4.25	5.68	-2.55	-1.33	-4.71	-6.02	-2.69	-0.94	8.51	-2.84	-1.88	-4.16	5.22	3.46	
Rank	4	2	9	7	13	14	10	6	1	11	8	12	3	5	

4. RESULTS AND DISCUSSION

Table 11 presents the ranking of hydropower projects obtained by TOPSIS, PROMETHEE II and ELECTRE III using eight sustainability criteria. Comparing the ranking of hydropower projects obtained using these four MCDM methods shows that alternative A_9 i.e., Sharavathi hydropower project obtained top ranking by PROMETHEE, and ELECTRE, whereas by TOPSIS it is on the second rank. But when comparing the values of R_i in TOPSIS, the value of R_i is very close for A_2 and A_9. Hence it can be concluded that Sharavathi hydropower (A_9) is evaluated as the most sustainable project under eight selected criteria for assigned weights. While comparing the complete ranking of all 14 hydropower projects, the three hydropower projects i.e., Sharavathi (A_9), Bhakra (A_2) and Upper Indravati (A_{13}) are on top three ranking by all four methods. All the methods gave somewhat different results with respect to the ranking position from 4-14 of the alternatives. The inconsistencies observed in the results of these methods are because of the differences in the calculation techniques, different interpretation of the criteria weights and the impact of the threshold values in the methods.

TOPSIS is based on the concept of compromise solution but their method of normalization is different. The PROMETHEE II and ELECTRE III are outranking methods which are based on the pairwise comparison and also allows the decision maker to express the preference in the form of threshold parameters. All the three MCDM methods are well adapted for ranking of hydropower projects considering both quantitative and qualitative features of criteria. The results produced by the different methods are usually different even considering the same problem with same input data. The need to take into account the factors like social, environmental, economic and technological in decision making for sustainability ranking of hydropower projects, make the process more complex. Hence MCDM methods have proved to be very helpful when there is a difficulty in selecting the best alternative while considering conflicting criteria and incomparable units. For future work, the proposed methods with the fuzzy environment can be applied to rank the hydropower projects and results can be compared.

Table 11. Ranking of hydropower projects from proposed methods

Ranking	TOPSIS	PROMETHEE	ELECTRE
1	A_2	A_9	A_9
2	A_9	A_2	A_2
3	A_{13}	A_{13}	A_{13}
4	A_5	A_{14}	A_1
5	A_1	A_1	A_{14}
6	A_{14}	A_5	A_8
7	A_{12}	A_{12}	A_4
8	A_7	A_7	A_{11}
9	A_3	A_6	A_3
10	A_8	A_{11}	A_7
11	A_4	A_8	A_{10}
12	A_6	A_4	A_{12}
13	A_{10}	A_3	A_5
14	A_{11}	A_{10}	A_6

5.   CONCLUSION

The present study demonstrates the effectiveness of TOPSIS, PROMETHEE II, and ELECTRE III methods to rank the hydropower projects based on eight sustainability criteria. AHP method is used to calculate the criteria weights. All these four methods are well adapted for sustainability assessment and ranking of hydropower projects considering conflicting criteria. The hydropower projects in the preference i.e., Sharavathi (A_9), Bhakra (A_2) and Upper Indravati(A_{13}) are ranked to be the most sustainable projects by the proposed methods. There is inconsistency in the complete ranking obtained by all these four methods even considering the same problem with same data is due to differences in the calculation techniques, the impact of the threshold values and the different interpretation of the criteria weights in the methods. Hence no single method can be categorized as best or worst, it depends on a certain application where some technique fits better. The study recommends PROMETHEE II and ELECTRE III for ranking since their flexibility allows the decision maker to express precisely the preferences for selecting the best alternative.

The application of MCDM techniques in ranking different renewable energy technologies and projects while considering several criteria and objective simultaneously has proved to be a reliable and realistic approach. Hence the paper highlights the potential of MCDM methods for multi-criteria analysis of any power project with stochastic nature (i.e., wind, solar, geothermal.) using quantitative as well as qualitative criteria.

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