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

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Abstract. Assessment of hydropower projects with respect to sustainability criteria is a multidimensional and complex issue. It requires considering technical, environmental, and social parameters instead of purely economic ones in decision making for energy planning. The flexibility to consider several criteria and objectives simultaneously leads to the use of multicriteria decision making (MCDM) methods which are well accepted in the field of energy planning. This paper aims at applying MCDM methods in facilitating the decision makers to select the most sustainable hydropower projects in the Indian region by making real and logical choices based on eight important criteria selected from the literature that are compatible with sustainable development. To comprehensively rank hydropower projects three MCDM methods are applied i.e., the 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). Analytic hierarchy process (AHP) is used to calculate the weights of criteria. All three methods are well adapted for sustainability assessment and ranked Sharavathi (A_9), Bhakra (A_2), and Upper Indravati (A_{13}) to be the most sustainable hydropower projects in India under the selected criteria. The study will be helpful in sustainable energy planning of hydropower projects with similar geographical conditions.

Keywords: hydropower projects, multicriteria decision making, ranking, sustainability assessment, sustainability criteria

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1. Introduction

Hydropower is recognized as a mature technology for electricity generation and is globally contributing towards the generation of renewable resources. Hydropower has a storage reservoir, which helps to meet the peak load demand and thus stabilizes the overall electrical grid [30]. Apart from generating low-cost electricity, hydropower provides water supply, flood control, drought management, recreation, irrigation, and job creation [8]. Regardless of these several advantages, the development of hydropower used to be highly controversial on account of its social and environmental impacts. These are loss of biodiversity, destroying of the ecosystem, greenhouse gas (GHG) emissions, submergence of large land area, displacement and resettlement of population, etc., [36]. Therefore, in the field of hydropower development, sustainability has become an important concern.

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Previously technical and economic parameters were the main criteria to analyze the hydropower projects that would mainly focus on electricity generation [11]. Later environmental and social aspects were also considered the significant criteria for sustainability assessment of hydropower projects [23]. Hence, it becomes necessary to consider all i.e., technical, economic, social, and environmental criteria for assessing the sustainability of hydropower projects. However, these criteria are contradict the design of an economical, high installed capacity hydropower project with negligible environmental and social impacts. Therefore, to tackle the hydropower system with a perception of sustainability as a complex problem, multicriteria decision making (MCDM) methods serve a quite realistic approach to solve problems that include conflicting criteria [25].

Several MCDM methods are widely applied in energy planning, sustainability assessment, and ranking of renewable energy projects such as hydropower, wind, solar, geothermal, etc. For example, run of river (RoR) hydropower projects were accessed based on sustainability criteria using analytic hierarchy process (AHP) [24], AHP is applied in [37] to study the potential to develop hydropower projects. To assist in energy planning [32] also used AHP to evaluate and rank the hydropower projects specifically to the hydropower plant constructions in the mountainous area of Italy. [2] used AHP to determine the most suitable site for a wind observation station. The preference ranking organization method for enrichment evaluations (PROMETHEE) method with fuzzy input data has been used in [18] to assess and rank alternative energy exploitation schemes of a low-temperature geothermal field, [40] applied PROMTHEE for ranking construction location of small hydropower. [19] used PROMETHEE for developing a framework for group consent on renewable energy projects, which was later applied to a geothermal reservoir project on the island of Chios.The elimination and choice translating reality (ELECTRE) method had been applied by [4] and [17] 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 [5, 13, 35]. 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 strength and weakness [22]. Hence no single method can be categorized as best or worst.

TOPSIS is based on the principle of fundamental ranking that the best alternative is closest to the positive ideal solution and farthest from the negative ideal solution [14]. It uses all allocated information and the advantage is that method need not require the information to be independent. However, the weakness of the method is that it works on the basis of Euclidian distance, therefore, it does not consider any difference between negative and positive values [22].

PROMETHEE method is characterized by ease of use and decreased complexity. It is based on the principle of outranking wherein the pairwise comparison of alternatives is performed to rank the alternatives with respect to a number of criteria [27]. It involves group-level decisions that deals with qualitative and quantitative information, can incorporate uncertain and fuzzy data besides allowing the decision maker to express the preference in the form of threshold parameters. But PROMETHEE is complicated and so users are limited to experts [22].

ELECTRE method is capable of handling discrete criteria of both quantitative and qualitative in nature and provides complete ordering of the alternatives. The analysis is focused on the dominant relations between alternatives. The outranking method uses the pairwise comparison between alternatives [33]. It can deal with heterogeneous scales and quantitative and qualitative features of criteria, and like PROMETHEE it also allows the preference in the form of threshold parameters. However, it is less versatile and requires a better understanding of objectives, especially when dealing with quantitative criteria.

Hence all three methods can be applied when required to deal with qualitative and quantitative criteria. When it is required to express a preference, PROMETHEE and ELECTRE find the best application. The above discussed all three ranking methods are most popular and well-accepted in sustainable energy planning [22]. Their advantages to deal with both qualitative and quantitative criteria makes them best suitable for the present assessment.

Many studies reviewed the sustainability criteria (indicators) for renewable energy for sustainable energy planning. As far as sustainability assessment of hydropower projects is concerned, some studies explicitly reviewed the sustainability criteria (indicators) for hydropower [23, 36, 38]. These studies have been referred for selecting the eight criteria based on techno-economic, economic, environmental, and social parameters. Sustainable development means satisfying present needs without compromising the ability of future generations to meet their own needs; wherein social, environmental, technical, and economic parameters all form the important pillars of sustainability [21]. To satisfy the present needs of society, assessment for techno-economic criteria, e.g., installed capacity, electricity generation per year, capacity factor, and most important economic criteria i.e., cost of generation become important [15, 37]. Since hydropower projects are often criticized over associated social and environmental impacts, displacement, safety, social benefits, and land use also form the essential criteria for assessment [23, 36, 38].

The present study demonstrates the application of the most often used MCDM methods namely TOPSIS, PROMETHEE II, and ELECTRE III on a practical example for ranking of major hydropower projects of India. The assessment is based on eight sustainability criteria that are perfectly compatible with sustainable development. The AHP method is used to evaluate the weights of the criteria. The approach developed is tested on a practical example focusing on the major hydropower projects in different regions of India, where displacement or resettlement were more than 4,000 people and having a large reservoir to make the problem more objective. As per the available literature and to the best of authors' knowledge these three methods have been applied for the first time to rank major hydropower projects of Indian region based on eight sustainability criteria.

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. AHP uses a multi-level hierarchical formation of objectives, criteria, sub-criteria, and alternatives.
The following steps are involved in the AHP method [29].

(i) Construct a pairwise comparisons matrix of the criteria involved in the decision using a numerical scale for comparison used in [32]. Let C_j $(j = 1, 2, \ldots, n)$ represents the jth criteria. B presents the (n x n) pairwise comparison matrix, where b_{ij} $(i, j = 1, 2, \ldots, n)$ 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 (W_i) is obtained by calculating the value of the geometric mean (GM_i) of i^{th} row.

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

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

(iii) Determine the matrix Y such that Y = B×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:

$$CV_i = \frac{C_i}{W_i} \tag{6}$$

(v) The value of the maximum eigenvalue λ_{max} is then calculated which is the average of the consistency values.
(vi) The value of the consistency index $(CI) = (\lambda_{max}\ \text{-}\ n)/(n\ \text{-}\ 1)$ 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 from [29] for the number of criteria. 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.

2.2. Methods for ranking of alternatives

2.2.1. The TOPSIS method

The TOPSIS method, developed by [20] comprises of the following steps:

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

$$\begin{array}{c} \\ \\ A_1 \\ A_2 \\ \ldots \\ A_n \end{array} \begin{array}{c} \begin{array}{cccc} C_1 & C_2 & \ldots & C_n \\ (W_1) & (W_2) & \ldots & (W_n) \end{array} \\ \begin{bmatrix} X_{11} & X_{12} & \ldots & X_{1n} \\ X_{21} & X_{22} & \ldots & X_{2n} \\ \ldots & \ldots & \ldots & \ldots \\ X_{m1} & X_{m2} & \ldots & X_{mn} \end{bmatrix} \end{array} \tag{7}$$

An element X_{ij} of the matrix indicates the performance rating of the i^{th} alternative A_i, with respect to the j^{th} criteria C_j, as shown in Eq. (7).
(ii) The normalized decision matrix r_{ij} of X_{ij} is calculated as defined in Eq. (8)

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

(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 the following equations:

$$V^+ = \left\{ \left(\sum_i^{max} v_{ij} / \ j \in J \right), \left(\sum_i^{min} v_{ij} / \ j \in J' \right) \ / \qquad i = 1,\ 2,\ \ldots,\ m \right\}$$
$$= \left\{ v_{1,}^+ \ v_{2,}^+ \ v_{3,}^+ \ \ldots,\ v_n^+ \right\} \tag{10}$$

$$V^- = \left\{ \left(\sum_i^{min} v_{ij} / \ j \in J \right), \left(\sum_i^{max} v_{ij} / \ j \in J' \right) \ / \qquad i = 1,\ 2,\ \ldots,\ m \right\}$$
$$= \left\{ v_{1,}^- \ v_{2,}^- \ v_{3,}^- \ \ldots,\ v_n^- \right\} \tag{11}$$

where $J = (j = 1, 2, . . ., n)/j$ is set of benefit criteria and $J' = (j = 1, 2, \ldots, n)/j$ is set of cost criteria.
(v) The separation between the alternatives can be calculated by the n-dimensional Euclidean distance. The separation of each alternative from the positive ideal solution is given as:

$$S_i^+ = \sqrt{\sum_{J=1}^{n} \left(v_{ij} - v_j^+\right)^2} \qquad i = 1, 2, \ldots, m \tag{12}$$

Similarly, the separation from the negative ideal solution is as follows:

$$S_i^- = \sqrt{\sum_{J=1}^{n} \left(v_{ij} - v_j^-\right)^2} \qquad i = 1, 2, \ldots, m \tag{13}$$

(vi) The relative closeness of the alternative A_{ij} from the ideal solution. is calculated as:

$$R_i = \frac{S_i^-}{S_i^+ + S_i^-} \tag{14}$$

(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 [7]. In the PROMETHEE method, a finite 'm' number of alternatives $A = [A_1,\ A_2,\ \ldots,\ Am]$ are evaluated for a finite 'n' number of evaluation criteria $C = [C_1,\ C_2,\ \ldots,\ C_n]$. PROMETHEE has proved to be an excellent tool for ranking considering multiple and complex criteria when dealing with the finite number of alternatives [16]. The versions available of PROMETHEE are PROMETHEE I, II, III, IV, V, VI, PROMETHEE GDSS, and GAIA (Geometrical Analysis for Interactive Aid). PROMETHEE I is used for the partial ranking; PROMETHEE II is based on comprehensive ranking; PROMETHEE III ranks based on the intervals; PROMETHEE IV for complete or partial ranking of the alternatives when the set of viable solutions is continuous; the PROMETHEE V for problems with segmentation constraints., the PROMETHEE VI for the human brain representation applied when the decision maker is not able or does not want to allocate precise weights to the criteria., the PROMETHEE GDSS for group decision making, and the visual interactive module GAIA for a graphical representation. Based on the user-friendly approach and mathematical property, each PROMETHEE method can be regarded as a convenient tool for decision making [6].

Among all the methods of this family, PROMETHEE II is the most acclaimed and frequently used one. It allows the 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 by a decision maker. The preference assigned is the value between '0-1'. The six preference functions had been proposed by [7], which are usual criterion (Type I) which is a linear preference function that takes values of '0-1'and limit from the right is zero, quasi criterion (Type II) which is almost similar to Type I except its limit from the right is not zero. (Type III) criterion is with linear preference and (Type IV) is level criterion. (Type V) is a criterion with linear preference and indifference area, and (Type VI) Gaussian criterion, for example, is nonlinear function.

Type I and Type IV are usually used for qualitative criteria, while the Type III and Type V preference functions are well adapted for quantitative criteria [12]. The selection between Type I or Type IV for qualitative criteria depends on the introduction of threshold parameters i.e., indifference threshold $(q_j)$and outright preference threshold (p_j) 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 [7]. Type I require fixing no parameters, while a selection of Type IV requires to fix q_j and p_j. Similarly Type III requires to fix only p_j and Type V requires to fix both q_j and p_j respectively for quantitative criteria.

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

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

where F_j represents the function of the deviation.
The index of preference $\prod\left(A_1,\ A_2\right)$ of alternative A_1 being preferred over alternative A_2 is given by Equation (16)

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

$\prod\left(A_1,\ A_2\right)$ is a number between 0 and 1 that represents the degree to which A_1 is preferred over $A_{2.}$

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

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

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

The positive outranking flow $\emptyset^{+}\left(A_1\right)$ in Equation (17) indicates how the alternative A_1 is outranking all the others, while the negative outranking flow $\emptyset^{-}\left(A_1\right)$ in Equation (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 Equation (19) is used to rank the alternatives. The highest rank will be assigned to the alternative with the greatest value of $\emptyset$.

2.2.3. The ELECTRE method

The ELECTRE method was first proposed by [33]. The method is based upon the outranking concept whereby an alternative A_1 outranks another alternative A_2 with enough fact existing 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. In the present study, ELECTRE III is selected for ranking the alternatives as this method provides an advantage of the direct participation of decision makers and a possibility to analyze both qualitative and quantitative criteria.

Let alternatives $A = (A_1,\ A_2,\ \ldots,\ A_m)$ are assessed for a finite n number of criteria (C$_1$, $C_2,\ \ldots,\ C_n$); $C_j\,(A_j)$ represents the performance of the alternative A for the criteria C_j $(j = 1, 2, \ldots, n)$.

The ELECTRE III ranking calculations involve following steps:

(i) The concordance index $C\,(A_1,\ A_2)$ is computed for each pair of alternatives:

$$C\,(A, A_2) = \frac{\sum_{j=1}^{n} w_j \quad C_j(A_1,\ A_2)}{\sum_{j=1}^{n} w_j} \tag{20}$$

where $C_j\,(A_1, A_{2,})$ is the outranking degree of the alternative A_1 and $A_{2,}$ under criteria j

$$C_j\,(A_1, A_2) = \begin{cases} 0 & if\ C_j\ (A_2) -\ C_j\ (A_1) \geq\ p_j \\ 1 & if\ C_j\ (A_2) -\ C_j\ (A_1)\ \leq\ q_j \\ p_j + C_j\,(A_1) - C_j(A_2)/p_j - q_j & otherwise \end{cases} \tag{21}$$

q_j and p_j *are* indifference and preference thresholds for the j^{th} criteria respectively.
Thus $0 \leq C_j\,(A_1, A_2) \leq 1$.
The relation between $q_j,\ p_j\ and\ \ v_j$ is as follows:

$$q_j <\ p_j <\ v_j \tag{22}$$

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, $C_j\,(A_2) >\ C_j\,(A_1) + v_j$.

(ii) The discordance index $d(A_1, A_2)$ for each criterion is then defined as follows:

$$d_j\,(A_1, A_2) = \begin{cases} 0 & ifC_j\,(A_2) - C_j\,(A_1) \leq\ p_j \\ 1 & if\ fC_j\,(A_2) - C_j\,(A_1) \geq v_j \\ C_j\,(A_2) - C_j\,(A_1) -\ p_j/v_j - p_j & otherwise \end{cases} \tag{23}$$

Thus $0 \leq d_j\,(A_1, A_2) \leq 1$

(iii) Finally, the degree of outranking is defined by $S\,(A_1, A_2)$:

$$S\,(A_1, A_2) = \begin{cases} C\,(A_1, A_2) & if\ d_j\,(A_1, A_2) \leq C\,(A_1, A_2)\ \ \forall j\ \epsilon\ J \\ C\,(A_1, A_2)\ \times\ \prod_{j \epsilon J(A_1, A_2)} \frac{1 - d_j(A_1, A_2)}{1 - C(A_1, A_2)} & otherwise \end{cases} \tag{24}$$

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 it requires to calculate the concordance credibility degree, the discordance credibility degree, and the net credibility degree:
(a) The concordance credibility degree is defined as:

$$\emptyset^{+}(A_1) = \sum_{B\ \in A} S(A_1, B), \ \forall A_1 \ \epsilon \ A \tag{25}$$

The concordance credibility degree measures the outranking character of A_1 i.e. how A_1 dominates all other alternatives of A.

(b) The discordance credibility degree is defined as:

$$\emptyset^{-}(A_1) = \sum_{B\ \in A} S(B, A_1), \qquad \forall A_1 \ \epsilon \ A \tag{26}$$

(c) The net credibility degree is then calculated as:

$$\emptyset(A_1) \ = \ \emptyset^{+}(A_1) \ - \ \emptyset^{-}(A_1) \tag{27}$$

The high value of the net credibility degree represents the 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 alternatives. The 14 major hydropower projects from various regions of India are carefully selected as alternatives with a focus on projects having installed capacity of more than 200MW, displacement or resettlement of more than 4000 people, and having a large reservoir to make the problem more objective. Table 1 presents the 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

Table 1: *List of selected hydropower projects*

3.2. Selection of evaluation criteria

The second step is very much critical under the MCDM approach i.e., the identification and selection of criteria to compare the alternatives. For sustainability assessment of renewable energy generation technologies, ranges of criteria should be considered [15]. The accessible information in terms of quantitative and qualitative data of alternatives will decide the selection of a number of criteria. The criteria selected in the present study for ranking of hydropower projects based on sustainability include, installed capacity, average electricity generation, capacity factor, cost of generation, land use, displacement of people, safety, and also social benefits. Table 2 presents the summary of the selected criteria and the criteria to be cost or benefit. This 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:

Criterion	Type	Unit	Benefit/cost criterion
Installed capacity (C_1)	Techno-economic	MW	Benefit
Electricity generation per year (C_2)	Techno-economic	MU/year	Benefit
Capacity factor (C_3)	Techno-economic	Percentage	Benefit
Cost of generation (C_4)	Economic	Paisa/KW	Cost
Land use (C_5)	Environmental	Hector	Cost
Displacement (C_6)	Social	Persons	Cost
safety (C_7)	Social	Qualitative (1-4)	Benefit
Social benefits (C_8)	Social	Qualitative (1-4)	Benefit

Table 2: *Summary of selected criteria [23, 35, 38]*

3.2.1. Techno-economic

The criteria selected in this type are installed capacity, annual energy production, and capacity factor. In the available literature, these criteria are merged with the economic criteria, whereas some have considered them in the technical or generation aspects [37, 39]. Therefore, in the present study, these selected criteria have been considered as techno-economic criteria.
(i) Installed capacity: In the present study installed capacity is a direct indication of the potential to generate power.
(ii) Electricity generation per year: Annual energy production directly improves the economy of power projects.
(iii) 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. The 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 the long-term success.
(i) Cost of generation: It is a major criterion with respect to the economic sustainability of the project. An economically sound project because of its low generation cost offers good investment opportunities [23].

3.2.3. Environmental

This criterion represents the project's environmental affinity with the surrounding region and ecology.

(i) Land use: The land use in the form of the reservoir may destroy the ecosystem. It results in the GHG emissions, soil erosion, silt deposition, obstruction to fish migration, etc. The land coverage in the form of flooding area of dam cause loss of farming plots, loss of spiritual places, and increases infectious disease [21].

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 [23].
(i) Displacement and resettlement: The main social impact of the construction of the large hydropower dam reservoirs is the displacement and resettlement of the affected communities. This forced displacement and the resettling process do not guarantee the same life for them that existed before. Hence from a sustainability point of view resettlement or displacement should be minimum.
(ii) Safety: As far as the safety of hydropower projects is concerned, the failure of dams caused by earthquakes remains a serious threat as they are capable to completely break the dam with the energy released from the event [26]. 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 on 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.
(iii) Social benefits: The benefits such as irrigation, flood control, recreation along with generation are also significant criteria from a sustainability point of view [15, 21]. The selected hydropower projects were scaled on (1-4) based on the benefits they are providing. For example, the hydropower projects which serve the purpose of only power generation were scaled as 1, and hydropower projects which serve the purpose of generation, irrigation, flood control, and recreation were scaled as 4 respectively.

3.3. Weights calculation of criteria by AHP

In our study, we selected 10 evaluators (4 academicians, 4 operations and maintenance manager of hydropower plants, and 2 project planning manager) who are well-versed expert in the domain of the problem to decide upon these weights, reflecting the importance of criteria in ranking the alternatives. The average weightage scale is calculated for each criterion, and finally, weights are calculated according to the steps explained in Section 2.1. Academicians were chosen to involve the attitude of public perception and to neutralizes the influence of other evaluators over any significant government energy policies adopted by the plant expert.

The public perception and recognition of any power technology play an important role along with expert opinion in the energy planning and decision-making process. However, public opinion may sometimes be biased because of lack of knowledge for a particular technology, under political influence or personal interest [31]. Therefore, expert opinion is of great importance, since experts while assigning weightag,e considered all the aspects of sustainability (social, environmental, economic, and technical). Table 3 presents the value of weights calculated as per the steps mentioned in Section 2.1. Using steps iv-vii mentioned in Section 2.1, the value of CR obtained is 0.0578 which is acceptable under limit $\mathrm{CR} \leq 0.1$. Therefore, there exists consistency in weights and can be used for the sustainability assessment.

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

Criterion	Criterion weight (W)
C_1	0.0368
C_2	0.2086
C_3	0.1818
C_4	0.3152
C_5	0.0867
C_6	0.0867
C_7	0.0292
C_8	0.055

Table 3: *Criteria weights calculated using AHP*

The highest weightage was assigned to the economic criteria C_4 (cost of generation) followed by C_2, C_3 (techno-economic criteria), C_5, C_6, C_8 (environmental and social criteria), and lastly C_1 (installed capacity) and C_7 (safety). Hydropower project's construction usually faces a lot of criticism because of the associated environmental and social impacts. Hence social and environmental criteria become important. The present study assessed the hydropower projects already commissioned and generating the power, hence the technical and economic parameters e.g., cost of generation, capacity factor, and net generation become more important.

3.4. Sustainability ranking of hydropower projects

The values of the selected criterion for hydropower projects (alternatives) are presented in Table 4 along with the weights calculated using AHP. Table 4 will be the input decision matrix to all the methods employed for sustainability ranking of the hydropower projects wherein C_1, C_2, C_3, C_7, C_8 are benefit criteria (larger the better), and C_4, C_5, C_6 are the cost criteria (smaller the better). Values of criteria (C_1, C_2, C_4, C_5, C_6) for selected hydropower projects are taken from [9, 10] and the values for criteria (C_3, C_7, C_8) are calculated as discussed in Section 3.2 using data from the website of the specific hydropower projects.

Alternatives	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 (W_j)	0.0368	0.2086	0.1818	0.3152	0.0867	0.0867	0.0292	0.055

Table 4: *Values for selected criterion for each selected alternative*

The ranking of the hydropower projects is based on the TOPSIS, PROMETHEE II, and ELECTRE III methods. As far as selecting the preference functions in the PROMETHEE II method is concerned, there is no general agreement about the choices of the preference functions and their effect on complete ranking [1]. Most of the research to date has tended to focus on the combination of six types of preference functions rather than one single preference function. Therefore, as discussed in Section 2.2.2 regarding the review of preference function, the present study, proposes the application of PROMETHEE II under the linear preference function (Type III) for the quantitative criterion and usual preference function (Type I) for the qualitative criterion. Table 5 presents the selected preference function and the values of thresholds i.e., q and p for each criterion for PROMETHEE II, and q, p, and v thresholds for ELECTRE III respectively. Based on the steps elaborated in Section 2.2.1, Section 2.2.2, and Section 2.2.3, Table 6 presents the final important values calculated in the TOPSIS, PROMETHEE II, and ELECTRE III methods.

Criterion	PROMETHEE preference function	PROMETHEE II thresholds		ELECTRE III thresholds		
		q	p	q	p	v
C_1	Linear	100	200	100	200	400
C_2	Linear	300	2000	300	2000	4000
C_3	Linear	5	15	5	15	30
C_4	Linear	20	100	20	100	200
C_5	Linear	2000	10000	2000	10000	20000
C_6	Linear	2000	10000	2000	10000	20000
C_7	Usual	n/a	n/a	0	1	2
C_8	Usual	n/a	n/a	0	1	2

Table 5: *Selected preference function and threshold parameters for PROMETHEE II and ELECTRE III*

Alternative	TOPSIS			PROMETHEE II			ELECTRE III		
	S_i^+	S_i^+	R_i	$\emptyset^+$	$\emptyset^-$	$\emptyset$	$\emptyset^+$	$\emptyset^-$	$\emptyset$
A_1	0.1126	0.2201	0.6616	0.6933	0.0628	0.6306	7.97	3.72	4.25
A_2	0.0129	0.2685	0.9543	0.6739	0.0992	0.5747	6.68	1.00	5.68
A_3	0.1348	0.2015	0.5993	0.5401	0.1357	0.4044	2.31	4.85	-2.54
A_4	0.1223	0.1626	0.5707	0.307	0.2075	0.0995	1.60	2.93	-1.33
A_5	0.1086	0.2369	0.6857	0.3092	0.2292	0.08	1.00	5.71	-4.71
A_6	0.1474	0.1946	0.5691	0.3332	0.305	0.0282	1.00	7.02	-6.02
A_7	0.1273	0.226	0.6396	0.2512	0.3036	-0.0525	3.15	5.84	-2.69
A_8	0.1265	0.1738	0.5787	0.2236	0.3333	-0.1097	1.00	1.94	-0.94
A_9	0.0225	0.265	0.9219	0.2261	0.3958	-0.1697	9.51	1	8.51
A_{10}	0.1888	0.1121	0.3726	0.2947	0.5149	-0.2202	1.01	3.85	-2.84
A_{11}	0.2321	0.108	0.3176	0.2646	0.4982	-0.2336	1.00	2.88	-1.88
A_{12}	0.1222	0.2326	0.6555	0.2469	0.4899	-0.243	1.95	6.11	-4.17
A_{13}	0.078	0.2297	0.7465	0.1875	0.4699	-0.2824	8.34	3.12	5.22
A_{14}	0.1223	0.2328	0.6556	0.1287	0.6349	-0.5062	7.13	3.67	3.46

Table 6: *Final important values calculated in TOPSIS, PROMETHEE II and ELECTRE III*

4. Results and discussion

Table 7 presents the ranking of the hydropower projects obtained according to the value of R_i in TOPSIS and values of ($\emptyset$) in PROMETHEE II and ELECTRE III as calculated in Table 6.

Ranking	TOPSIS	PROMETHEE II	ELECTRE III
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

Table 7: *Ranking of hydropower projects from TOPSIS, PROMETHEE II and ELECTRE III*

Comparing the ranking of the hydropower projects obtained using these three MCDM methods, shows that alternative A_9 i.e., Sharavathi hydropower project obtained top ranking by PROMETHEE II, and ELECTRE III, 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 the eight selected criteria for the 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 the top three rankings by all three methods. All three methods gave somewhat different results with respect to the ranking position from 4-14 of alternatives even with the same input data. The inconsistencies observed in the results of these three methods are because of the differences in the calculation techniques and the impact of the threshold values in the methods.

All three MCDM methods are well adapted for ranking hydropower projects considering both quantitative and qualitative features of criteria. The need to consider 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 difficulty in selecting the best alternative while considering conflicting criteria and incomparable units.

The PROMETHEE II and ELECTRE III have added advantage since their flexibility allows the decision maker to express precisely the preferences for selecting the best alternative. The previous studies, e.g. [26, 40] found PROMETHEE II well adapted in ranking and sustainability assessment and energy planning. However, the study [34] prefers ELECTRE III over PROMETHEE in context to environmental problems. Similarly, the study [3] found ELECTRE III suitable for site ranking, and [38] concluded that ELECTRE III, is an empirical and feasible approach for supporting power distribution system planning. The review study [28] on application of MCDM on sustainable energy planning concluded PROMETHEE and ELECTRE as the most popular method after AHP. For future work, the proposed methods with the fuzzy environment can be applied to rank the hydropower projects and results can be compared.

5. Conclusion

The present study demonstrates the effectiveness of TOPSIS, PROMETHEE II, and ELECTRE III methods to rank the major hydropower projects of the Indian region based on the eight sustainability criteria. AHP method is used to calculate the criteria weights. All these three methods are well adapted for sustainability assessment and ranking of hydropower projects considering conflicting criteria. The hydropower projects 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 under selected criteria and assigned criteria weights. There is inconsistency in the complete ranking obtained by all these three methods, even considering the same problem with the same data. It is due to differences in the calculation techniques and the impact of the threshold values 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 study will be helpful in sustainable energy planning of hydropower projects with similar geographical conditions.

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

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