

# Application of Multi-criteria Decision Aids for Selection of Off-Grid Renewable Energy Technology Solutions for Decentralised Electrification

Dattakiran Jagu, D. Pugazenthi and V. V. N. Kishore

**Abstract** This chapter demonstrates a multi-stakeholder approach for selection and ranking of renewable energy technologies for decentralised electrification in India by using PROMETHEE, a multi-criteria decision aid. A graphical descriptive analysis is applied to map the various conflicts observed and to suggest possible interventions. The results show that micro-hydro is currently the best compromise solution for decentralised electrification in India, followed by biomethanation. A substantial investment in technology standardisation of biomass technologies and associated sub-systems and significant reduction of the costs of PV-based technologies are required before they can be adopted on a wider scale. Innovative hybrids and smart mini-grids can be used in the short term for diversity in supply options.

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## 1 Introduction

The lack of access to modern energy services acts as a severe impediment to human development [19, 42] and ensuring energy access is one of the major challenges developing countries face today. The percentage of the population not using electricity or commercial energy is one of the most crucial indicators to energy access [22]. With over 1.3 billion people—primarily in sub-Saharan Africa and developing Asia—still lacking access to electricity [24] and possibly an even larger number having only intermittent access to power, the task of supplying them reliable and affordable electricity is formidable. The conventional resources that would be required to achieve this are equally enormous.

The IEA estimates that a cumulative investment of \$1 trillion— an average of \$48 billion per year, is required to achieve the target of universal energy access by 2030 [6]. About 90 % of this cost is estimated for electrification alone. In a similar study, Bazilian et al. [2] have estimated that till 2030, the annual cost of universal access to electricity would be between \$12 and \$134 billion. These are only a tiny fraction of the global investment required in energy infrastructure [6]. This kind of additional investment would be a very heavy burden for developing countries. This obligates funding agencies, government bodies and private investors to make judicious choices by adopting the right solutions that target the most energy-poor while ensuring the long-term sustainability of these solutions.

Decentralised/distributed generation systems, often using renewable energy technologies (RETs) have the flexibility in size, fuel and technology choice, capability to produce reliable power [23] and ability to induce local energy autonomy. However, RETs vary immensely in terms of the resources required, their initial and operational costs, perceived social and environmental benefits and their levels of technical maturity.

In spite of such problems in decision-making, RETs have been tried out in several developing countries for off-grid electricity generation. Micro-hydro in Nepal, solar photovoltaic (PV) home lighting systems in Bangladesh, India, Philippines and Kenya, biomass systems based on gasification, anaerobic digestion and bio-diesel in India, Sri Lanka and Cambodia and miscellaneous hybrid systems in India are some examples. Both micro-hydro and PV systems have been chosen primarily for their technology maturity and reliability. PV systems have especially been promoted with a conviction that increased productions will ultimately reduce the cost. Biomass technologies, on the other hand, were primarily selected because of reliability of local resources, lower initial costs and possibility of meeting electricity-intensive load demands such as irrigation, flour milling, and oil expelling at a lower cost. Unfortunately, experiences (both positive and negative) with hundreds of such field installations have not led to clear directions for future funding or promotional policies, investments in technology/product development, focus on applied R&D and regulation. The application of a multi-criteria approach and the use of multi-criteria decision aids (MCDA) for sustainable development decisions fosters integration of the stakeholders, makes the decision process fair and democratic and legitimises the results of decision [37].

The objective of this study is to demonstrate the identification of suitable renewable energy technologies for decentralised electrification in India using multi-criteria decision aid and also to understand the future R&D or financing needs for other promising technologies. This study has been confined to those RETs that have at least one working decentralised installation in India. This has led to shortlisting of the following technology options: micro-hydro, solar PV, biomass gasification, wind-PV hybrid and biomethanation.

It is proposed to adopt a top-down approach driven by a single problem of seeking the most suitable renewable energy technology, which is further decomposed into dimensions and objectives. The extent to which a particular RET fulfils each objective is measured with respect to one or more criteria. Next is to identify the various dimensions that need to be considered for taking a decision on a decentralised electrification project. Field visits conducted in six states spread across India and face-to-face discussions held with project developers, technical experts, non-governmental organisations and end-users gave an insight into some important factors considered by them for setting up and operation of decentralised projects. These factors fell broadly into the following categories: Environmental, Social, Economic, Resource, Technical, Operational and Regulatory.

The study has been validated by a multi-criteria decision aid PROMETHEE (Preference Ranking Organisation Method for Enrichment of Evaluations). A graphical descriptive analysis is applied to map the various conflicts and to suggest possible interventions.

## 2 Earlier Studies for Comparison and Selection of RETs

There is a well-developed body of literature featuring studies on performance evaluation and selection of appropriate renewable energy options. A rich diversity can be observed within these studies based on their focus of evaluation and the analytical approaches employed.

The studies can be hierarchically arranged into those that focussed on: (a) Techno-economic characteristics such as cost of energy, energy potential, life cycle cost, reliability of supply, and exergy [13, 21, 26, 31, 34–36, 40, 46]; (b) Social, Economic and Environmental impacts [3, 12, 16, 28, 41, 48]; and (c) Sustainability attributes [1, 14, 27, 38, 50]. Techno-economic evaluations, that form the bulk of these studies, can help the decision-maker in appreciating the technical and economic implications of a particular choice. The studies based on social, economic and environmental impacts alone fail to emphasise the importance of an existing local ecosystem. Studies that additionally focussed on the operational sustainability included sustainability of the technology during and beyond the lifetime of the project.

A further classification of the evaluation studies can be made based on the approach used to analyse the energy options. Evaluations based on a single criterion such as cost of energy are easier to analyse but could be inadequate for

decision-making. A slightly more complex approach involves optimisation [31, 48] or a break-even analysis [34] involving two or more criteria. Variations include those that seek the optimal mix of RETs [26] when subject to input constraints. However, this approach fails to consider multiple perspectives of different stake holders, especially the end-users. A multi-stakeholder and multi-criteria approach that captures the stakeholder priorities and adopts a rational analysis method can lead to a wider consensus among the stakeholders. This, when combined with a participatory approach [14, 38] that considers the aspirations and constraints of the local communities can result in a more credible solution [5] and can build their trust in decisions and political institutions [43].

Many initial studies were based on single-criterion approach focusing primarily on the techno-economic dimension, which have been sometimes used to promote a 'favourite' technology. For example, techno-economic studies for remote village electrification in India justified the high initial investment in PV systems compared to the cost of extending the grid. However, PV systems have often provided limited electricity supply and did not meet all the current and future needs, especially irrigation in most cases. While it may be technically possible to design PV systems to meet the entire demand, the cost of doing so is likely to be very high, thereby requiring longer pay-back periods and making the cost of supply beyond reach of many consumers.

By employing analytical techniques, some studies aimed to identify the most favourable technology or a single best-optimised solution within their decision context and to suggest policy recommendations for its choice. For example, Kaya and Kahraman [28] employed a fuzzy multi-criteria decision-making technique to identify that wind energy is the most appropriate technology for Istanbul region and that Çatalca district is the best area for installing the wind turbines. Few studies went further to investigate the market mobilisation and technology transfer of the identified technology [16] or to explore newer technical opportunities [21]. A critical gap found in many studies is that the prescriptive approach adopted for solving the decision problem fails to depict the inter-dimensional and inter-perspective conflicts involved in the decision-making. Another key missing element in most studies is that they often stopped short of suggesting remedial measures or policy recommendations for the technical advancement of the non-best solutions.

## 3 Methodology

### 3.1 Multi-criteria Decision Aids

Multi-criteria decision analysis or multi-criteria decision aids (MCDA) evolved as a response to the inability of people to effectively analyse dissimilar information from multiple disciplines [30]. They can provide the concepts and guidelines for structuring and modelling decision problems [45], thereby aiding the decision-making

process in developing suitable criteria, in gaining acceptance of stakeholders and in creating new ideas for solutions [37]. With no right solution independent of the decision process [44], the decision taken can be only as legitimate as the underlying MCDA technique.

### ***3.2 Selecting an MCDA Technique***

Numerous MCDA techniques and their classifications have been comprehensively studied in various literatures [4, 17, 20, 47]. Despite the large number of MCDA techniques, none is perfect [33] and the success or failure of a particular technique depends primarily on the context in which it is being applied. A comparison of the MCDA methods revealed that the most crucial quality criteria are the method's ability to deal with complexity, possibility to consider non-substitutability, ability to invoke stakeholder participation and ability to provide information to stakeholders to make better decisions [15]. For RET selection, Polatidis et al. [39] recommend that an analyst should necessarily consider the technique's treatment of the sustainability issue, modelling of the decision matrix preferences, technical features, treatment of uncertainty and consideration of practical aspects such as ease of use, ability to handle multiple criteria, qualitative inputs and support for multiple decision matrices. In our context, we chose to apply PROMETHEE—an outranking method, along with a multi-stakeholder approach in identifying the criteria for evaluation, prioritising amongst them and then evaluating the RETs.

There are at least four reasons for choosing PROMETHEE for this study. First, it is flexible in accepting poorly shaped stakeholder inputs such as environmental, economic and social impacts of the RETs. Second, both qualitative and quantitative data can be dealt with simultaneously, each in its own units. Third, it can provide two types of rankings—with and without incomparability amongst the RETs, which helps in appreciating the relative strengths and weaknesses of each RET. Finally, by using the GAIA (Geometrical Analysis for Interactive Aid) tool, it permits a visual depiction of the decision problem which aids in a better understanding of the inter-dimensional and inter-stakeholder synergies and conflicts thereby ensuring debate and consensus building among the stakeholders.

### ***3.3 PROMETHEE and GAIA***

PROMETHEE [7, 8, 10, 11] is an out-ranking technique typical of the European school of MCDA. It is based on the principle of pair-wise comparison of the alternatives. After forming an evaluation matrix of performance of alternatives on all the criteria, the PROMETHEE process involves:

**Table 1** Types of preference functions

Preference function	Remarks
Usual preference function	Simple, does not include any threshold, best suited for criteria with a few very evaluation criteria
U-shape preference function	Introduces the idea of an indifference threshold
V-shape preference function	Special case of the Linear preference function where the $Q$ indifference threshold is equal to 0, well suited to quantitative criteria when even small deviations should be accounted for
Level preference function	Suited to qualitative criteria when the decision-maker wants to modulate the preference degree according to the deviation between evaluation levels
Linear preference function	Best suited for quantitative criteria when a $Q$ indifference threshold is wished
Gaussian preference function	An alternative to the Linear, has smoother shape but it is more difficult to set up because it relies to a single $S$ threshold that is between the $Q$ and $P$ thresholds and has a less obvious interpretation

### 3.3.1 Assigning a Preference Function to Each Criterion

The preference functions translate the difference of performance of alternatives on a given criterion in terms of a preference degree measured between 0 (no preference) and 1 (absolute preference). Six possible types of preference functions (Table 1) [11] can be assigned by the decision-maker, each representing a different perception of measurement scales for criteria.

### 3.3.2 Assigning Weights to the Criteria

No specific guidelines exist in PROMETHEE for determining weights to the criteria. A simple method of calculating weights by pair-wise comparison of criteria used in Kohli et al. [29] has been adopted in this chapter. When weights calculated for each of the stakeholders are averaged out, this method prevents any one individual's judgment to dominate the process.

### 3.3.3 Estimating the Outranking Degree of Options

Using the criteria weights and preference functions, a multi-criteria preference index  $\pi(a, b)$  is computed as the weighted average of the preference functions  $P_j(a, b)$ .

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

where,  $w_j > 0$  is the normalised weight allocated to the  $j$ th criterion (the more important the criterion, the larger  $w_j$ ), and  $P_j(a, b)$  is the value of the preference function for criterion  $j$ th criterion when action  $a$  is compared to action  $b$ .

$\pi(a, b)$  is a number between 0 and 1. It expresses how much ‘ $a$ ’ is preferred to ‘ $b$ ’ taking into account all the criteria and their weights.

The positive flow (strength)  $\Phi+$  expresses how much an alternative is dominating the other alternatives and the negative flow  $\Phi-$  expresses how much it is dominated (weakness) by the others. A higher value of  $\Phi+$  or a lower value of  $\Phi-$  indicates better performance. Positive and negative flows usually induce somewhat different rankings of the alternatives. The net flow  $\Phi$ , which is the balance between the positive and negative flows, defines the net outranking.

$$\Phi + (a) = \frac{1}{n - 1} \sum_{b \neq a} \pi(a, b)$$

where: alternative ‘ $a$ ’ is dominating the other  $n-1$  alternatives.

$$\Phi - (a) = \frac{1}{n - 1} \sum_{b \neq a} \pi(b, a)$$

where:  $n - 1$  alternatives are dominating alternative ‘ $a$ ’.

$$\Phi(a) = \Phi + (a) - \Phi - (a)$$

Two main PROMETHEE methods have been used to rank the RETs:

- PROMETHEE I—provides a partial ranking based on  $\Phi+$  and  $\Phi-$  and permits incomparability between the alternatives.
- PROMETHEE II—provides a complete ranking based on  $\Phi$  assuming comparability amongst all the alternatives.

The prescriptive (ranking) approach of PROMETHEE is complemented by a descriptive (visual) approach called Geometrical Analysis for Interactive Aid (GAIA). GAIA involves computation of uni-criterion net flows by normalisation and projecting them onto a plane for visual analysis. The two-dimensional representation of multi-criteria data and of the technology profiles helps to identify conflicts among criteria, fix the priorities and seek possible compromise solutions. A detailed discussion regarding the PROMETHEE methods and GAIA analysis can be found in [9, 32].

### **3.4 Visual PROMETHEE Software**

Visual PROMETHEE is a up-to-date software implementation of the PROMETHEE and GAIA multi-criteria decision aid (MCDA) methods. It is developed by Professor Bertrand Mareschal from the Solvay Brussels School of Economics and Management of the Université Libre de Bruxelles (ULB). An academic edition of Visual PROMETHEE software has been used for this study.

### **3.5 Method of Ranking**

The first step is to identify the key stakeholders who would be involved in decentralised energy planning. Franco and Montibeller [18] defined key stakeholders as those individuals, or groups, who have the power to affect the decision under consideration; or those groups that are affected, or perceived to be affected, by the decision. The following types of key stakeholders in developing countries are initially identified: project developers, technology experts, policy makers in government bodies, international donor agencies, private sponsors and the local citizens. Inclusion of project developers and private sponsors with prior experience in RET installations increased the legitimacy of the decision, and inclusion of technical experts increased its technical competency. Inclusion of international donor agencies brought in their expertise in similar contexts. Policy makers contributed to the political and regulatory perspective of the decision. In addition, discussions with the local citizens are helpful in capturing the aspirations of local communities and therefore to develop suitable criteria that measure the ability of RETs to fulfil these aspirations.

The methodology given in Fig. 1 was used for our purpose to rank the RETs. The sequential process makes it simple and easy to follow each step and the recursive steps improve the quality of decision.

Minimum inputs in the form of available alternatives, evaluation criteria and their relative importance are required from the experts. Subjectivity is eliminated with the formation of a decision matrix which captures all the inputs, thus making the process objective and transparent. Iterations during performance evaluation help in judging the most important alternatives, while eliminating the clearly inferior ones. This leads to a compact decision matrix and lesser information for the decision-maker to comprehend. To account for uncertainty in the experts' opinions and to handle the evolving nature of the technology development and variations in costs, a sensitivity analysis was proposed for the results obtained.



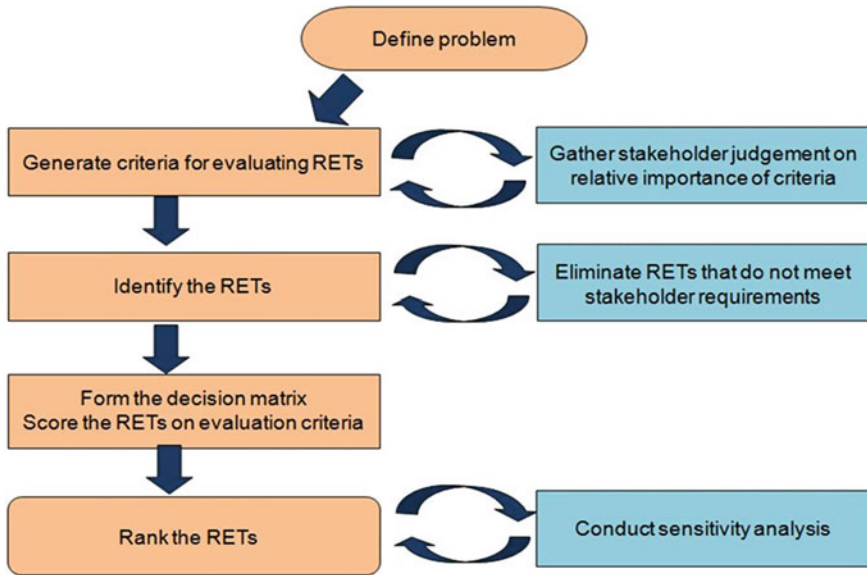


Fig. 1 Ranking methodology

### 3.6 Generation of Evaluation Criteria

In the review of MCDA techniques, Wang et al. [49] identified at least 25 criteria, broadly categorised into Technical, Economic, Environmental and Social indicators. For studies on rural electrification, Ilskog [25] proposed 39 indicators, grouped under five dimensions: Technical, Economic, Social/ethical, Environmental, and Institutional sustainability. Karger and Hennings [27] compiled 86 sustainability criteria, arranged in the form of a value tree to evaluate different explorative scenarios of decentralised electricity generation.

From the reviews, efficiency and reliability of service and technology maturity are clearly the most widely used technical indicators. Among the economic indicators, capital cost, operational and maintenance (O&M) cost and cost of energy (CoE); and among the social indicators, contribution to local employment and social acceptance are the ones often used. Reduction of greenhouse gas (GHG) emissions and land use were the oft-used environmental indicators.<sup>1</sup> Other critical indicators included the availability of the renewable energy resources and availability of human resource for operating and servicing the technology.

Discussions with local citizens in remote unelectrified and partly electrified villages in three underdeveloped states of India further revealed that factors such

<sup>1</sup> However, this does not necessarily cover all environmental damages. For example, toxic waste water from biomass gasification system is a problem but the environmental indicator has not covered this aspect.

as the number of jobs provided to locals in the construction and operation of the project, involvement of women and equity in supply are among the most important social benefits perceived by them. Few citizens also opined that the quality of electricity supply needed to run productive loads or appliances that reduce their drudgery is at least as important as the number of hours of supply.

The evaluation criteria chosen for our study, the factors used for their construction/measurement and the scales of measurement are given in Table 2. The criteria are chosen so as to incorporate all the important dimensions of the decision while ensuring the relative independence of each criterion.

### ***3.7 Prioritisation of Evaluation Criteria***

Once the evaluation criteria are identified, the next step was to prioritise amongst them. For this, it was essential to invoke the participation of key stakeholders who have an insight into all the facets of the criteria and the different viewpoints of the problem. Four relevant policy makers in central and state governments, one representative of an international donor agency, three project developers and four private sponsors of existing projects were identified from multiple geographic locations in India to conduct the interviews.

#### **3.7.1 Interviews with Key Stakeholders**

The 12 key stakeholders identified were interviewed either face-to-face or over the phone with a written survey questionnaire (Table A.2) to elicit their opinion on the relative importance of the criteria. Semi-structured interviews were conducted in a conversational format. Care was taken to ensure that there was a fair representation from rural areas and that the stakeholders were randomly identified from different states in India. Due to time and resource constraints, a full-scale survey was not possible. The prioritisation process in our study can only provide an overview of varied stakeholder priorities. Therefore, further sensitivity analysis of stakeholder priorities was done to analyse the stability of the rankings obtained.

The goal was to compare all the alternatives pair-wise and assign a weight coefficient to each of them. To enable easier comparison, the questionnaire was formed such that the stakeholder could enter the priorities on a scale of 1 (highest priority) to 10 (least priority) or could categorise the criteria into five categories of importance—Very high, High, Medium, Low, Very low.

#### **3.7.2 Analysis of Survey Results for Prioritisation of Criteria**

It was observed that the different stakeholders displayed a great deal of variation on some criteria, while some criteria are consistently given similar priority by all


**Table 2** Evaluation criteria

Criteria	Scale	Factors assessed
Environmental benefits	Qualitative	Reduction in CO <sub>2</sub> and reduction in environmental degradation
Social benefits	Qualitative	Jobs to local people in construction and operation, increased income/productivity, improvement in health, safety and education, involvement of women in operation
Resource availability and variability	Qualitative	Availability of energy resource in the specific region, its variability during the day and throughout the year
Initial capital cost (ICC)	Numerical	Cost of Equipment, civil works, battery storage, wiring and installation cost, T&D lines
Operation and maintenance cost (O&M)	Numerical	Costs for fuel, labour, servicing and battery replacement
Technology maturity	Qualitative	Number of technology providers in the country, availability of standards, status of R&D, ease of use
Technology performance	Qualitative	Ability to handle high-powered loads, plant load factor (PLF)
Supply chain availability	Qualitative	Availability of local manufacturing, local availability and cost of spares and service
Operational sustainability	Qualitative	Availability of stable quality and quantity of fuel/feed stock throughout the lifetime of the project, availability of human resource for operation, scalability of technology
Policies and Regulations	Qualitative	Policies favouring decentralised electrification (subsidies available for different technologies, different schemes implemented in the past), environmental regulations, policies for promoting private enterprise

the stakeholders. This high variation in stakeholder priorities (Table 3)—particularly of criteria such as social benefits, environmental benefits and policies and regulations clearly depicts the conflicting views among the various groups of stakeholders and the subjective nature of their opinions.

After each survey, weights were calculated for each criterion using a method adopted from Kohli et al. [29]. A weight is obtained for each criterion by first establishing a rank order for the criteria and then converting this into quantitative weights by pair-wise comparison in an  $N \times N$  matrix. This method requires relatively simpler calculations and permits inconsistency in priorities between varied types of stakeholders. An example for calculation of weights is provided in Table A.1. To handle the variations in the priority rankings and to arrive at a single weighting of the criteria, the weights obtained from all the stakeholders’ surveys were averaged.

**Table 3** Differences in stakeholder priorities

Priority level	Criteria	Mean priority	Standard deviation
 High	Resource availability and variability	3.83	1.79
	Initial capital cost	4.00	2.73
	Technology performance	4.5	1.78
	Operation and maintenance cost	5.08	2.19
	Operational sustainability	5.5	2.15
	Technology maturity	5.58	2.35
	Environmental benefits	5.33	4.12
	Social benefits	5.67	3.42
	Supply chain availability	6.67	2.42
	Low	Policies and Regulations	7.5

### 3.8 Identification of RETs

The following RETs have been tried out for off-grid electricity generation in South Asia: micro-hydro, solar PV, biomass gasification and biomethanation. Combinations of a few of the RETs were also tried in some instances. For limiting our study to a finite number of RETs, we chose to include only one hybrid: Small wind turbine—Solar PV hybrid in our study. The RETs identified for our study are mentioned in Fig. 2.

Solar home systems and small wind home systems, though ideal for individual homes and battery charging stations, cannot be considered for mini-grids. Due to their inherent characteristic, they are not capable of generating enough power to cater to the demands of an entire village/hamlet. Hence, these two alternatives are dropped from further analysis.

### 3.9 Formation of a Decision Matrix and Scoring of RETs

Once the alternatives are determined, the next step is to evaluate the alternatives for the criteria defined. Data is obtained by field visits to many working installations for decentralised electrification in India and one installation in Nepal (Table 4).<sup>2</sup> Various stakeholders such as technology experts, project developers and NGOs who were responsible for the installation and operation are asked to rate the particular technology in which they have experience/expertise. Where criteria could not be quantitatively measured, suitable qualitative scales with nine levels of measurement are constructed.

<sup>2</sup> The visited sites are not necessarily rural electrification projects although they relate to decentralised electrification.

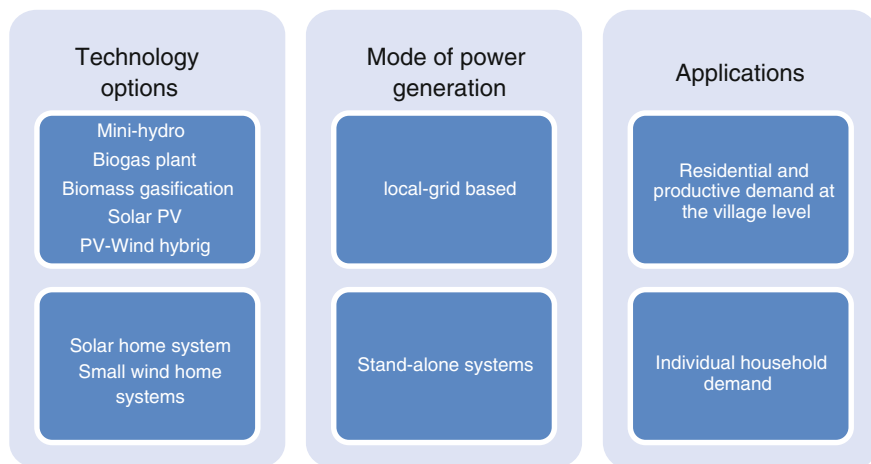


Fig. 2 RET options identified

Table 4 List of decentralised electrification sites visited

SI. No.	Site location	Technology used	Capacity of the plant (kW)
1	Mandya, Karnataka, India	Wind-PV	5
2	Radhapur, Madhya Pradesh, India	Biomass gasification	10
3	Jabalpur, Madhya Pradesh, India	Biomethanation	10
4	Kasdol, Chattisgarh, India	Solar PV	3
5	Sanawadia, Madhya Pradesh, India	Wind-PV	2
6	Bangalore, Karnataka, India	Solar PV	100
7	Kabbigere, Karnataka, India	Biomass gasification	500
8	Satna, Madhya Pradesh, India	Biomethanation	50
9	Bhavanipatna, Orissa, India	Micro-hydro	12
10	MalekhuKhola II, Mahadevsthan VDC, Dhading, Nepal	Micro-hydro	26

At least two installations for each RET identified for our study was visited. The capital costs obtained excluded any subsidies, because subsidies vary for different projects. As subsidies distort the decision-making process, the subsidy component has been removed from the analysis. To remove discrepancies in costs due to variation in plant capacity, the capital costs and the monthly operational expenses are calculated per unit size of the plant. Further, since the site conditions are not always uniform, the two sets of scores obtained for each RET are averaged to obtain one score per criterion. The RETs to be evaluated and the criteria on which they are evaluated are arranged in rows and columns to form a decision matrix. The decision matrix thus constructed is given in Table 5.

**Table 5** Decision matrix

	Units/scale	Solar PV	Micro-hydro	Biomethanation	Biomass gasification	Wind-PV
Resource availability and variability	(1–9)	7	8.5	8.5	4.5	7
Environmental benefits	(1–9)	8.5	9	8.5	9	9
Initial capital cost (ICC)	\$/kW	5277.78	3787.44	3222.22	1194.44	5833.33
Technology performance	(1–9)	3.5	8	7	7	6
Social benefits	(1–9)	6	9	7	8	7
O&M costs	\$ kW <sup>-1</sup> month <sup>-1</sup>	30.93	6.56	22.22	18.18	44.44
Technology maturity	(1–9)	7.5	8	3.5	6	8
Operational sustainability	(1–9)	7.5	8.5	8	6.5	7.5
Supply chain availability	(1–9)	6	6	6.5	4	5.5
Policies and regulations	(1–9)	7.5	7	2	3.5	5

Source Field visits (Note A conversion of 1 USD = 45 INR)

The decision matrix consists of qualitative and numerical parameters. The numerical parameters such as initial capital cost and O&M costs have been obtained from the field visits, while all other parameters are qualitative in nature.

## 4 Results and Discussion

### 4.1 Ranking of the RETs

With the decision matrix and the criteria weights as inputs, PROMETHEE analysis is performed using Visual PROMETHEE software. A ‘preference function’ is then assigned to each criterion in order to model the way the decision-maker perceives the measurement scale of the criterion. The purpose of the preference function is to translate the deviation in scores to a preference degree between 0 and 1: 0 means no preference at all and 1 means an absolute preference.

Preference functions with multiple levels of preference are assigned to each criterion. Indifference and preference thresholds are defined for a few criteria such as costs, technology maturity and supply chain availability, so as to factor in their ever-evolving nature and also the subjective nature of the stakeholder judgements.

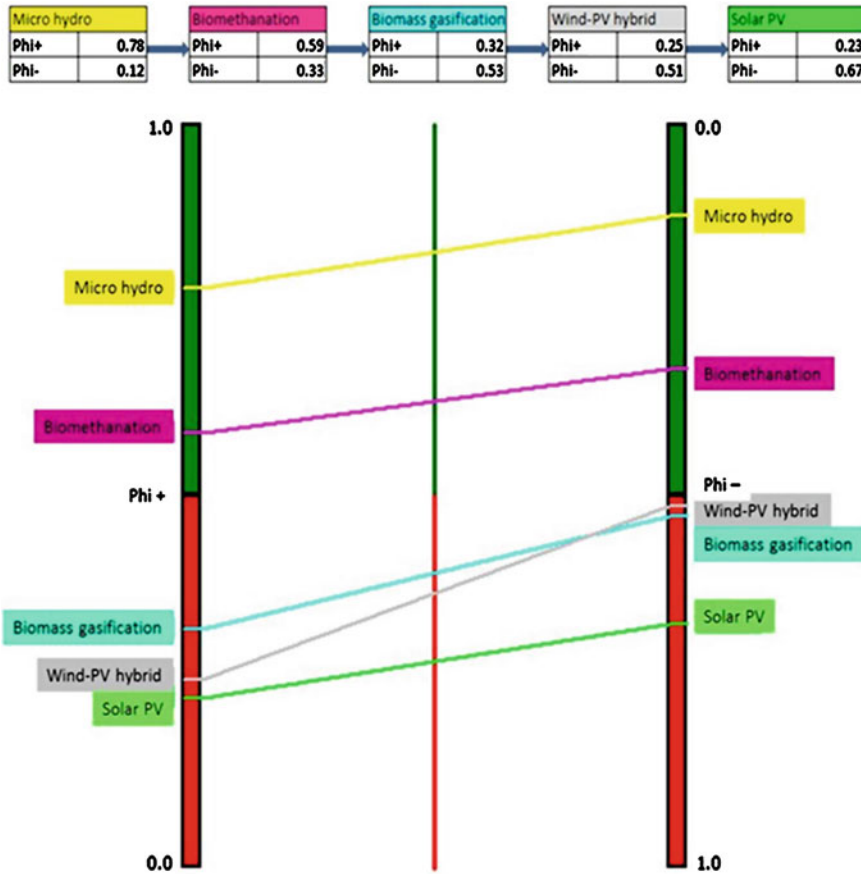


Fig. 3 PROMETHEE I ranking

In the PROMETHEE I Partial Ranking (Fig. 3), the leftmost bar shows the ranking of the RETs according to  $\Phi+$ : Micro-hydro is on top, followed by Biomethanation, Biomass gasification, Wind-PV hybrid and Solar PV. The rightmost bar shows the ranking according to  $\Phi-$ : Micro-hydro is still on top, followed by Biomethanation. But it is now followed by Wind-PV hybrid, Biomass gasification and Solar PV. PROMETHEE I provides a partial ranking based on the positive ( $\Phi+$ ) and negative ( $\Phi-$ ) flows of the alternatives. PROMETHEE II (Fig. 4) provides a complete ranking based on the net flow ( $\Phi$ ).

Visual PROMETHEE software allows simultaneous viewing of both rankings using a two-dimensional diamond-shaped representation (Fig. 5). Inside the PROMETHEE Diamond, the RETs are placed based on their relative strengths ( $\Phi+$ ) and weaknesses ( $\Phi-$ ). The two axes are angled such that each RET is a cone. The intersection of the two flows gives the partial ranking and the projection

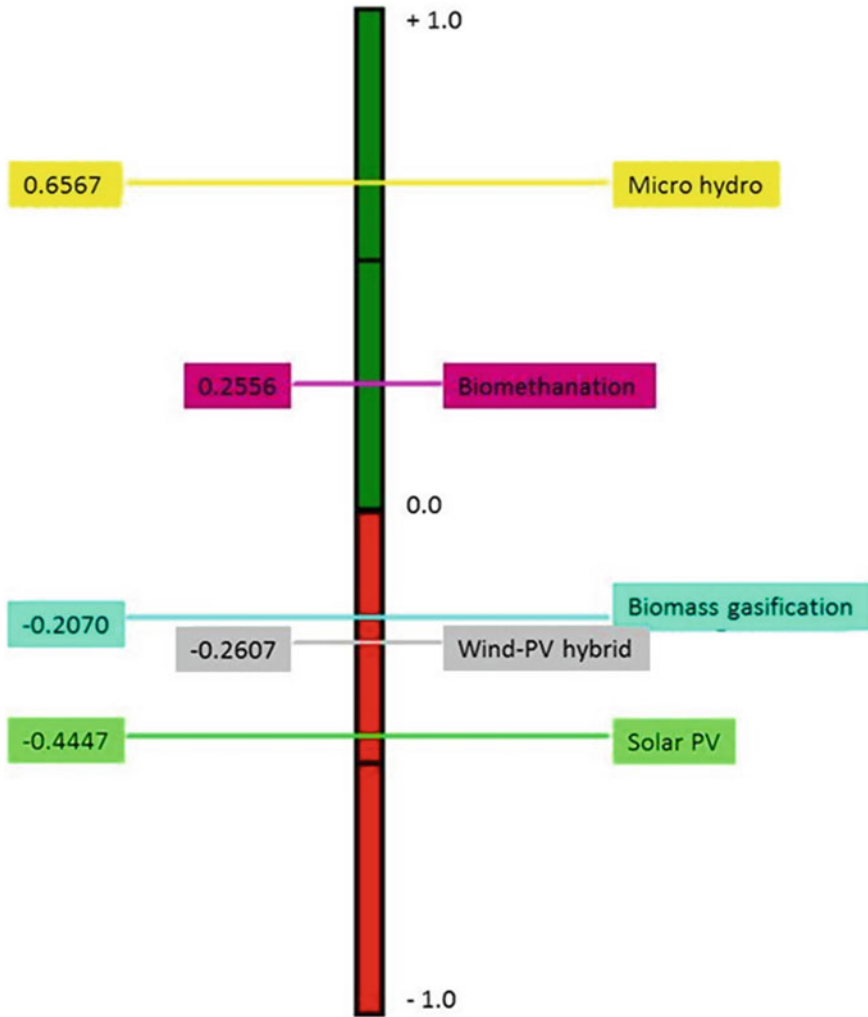


Fig. 4 PROMETHEE II complete ranking

of the meeting on a vertical axis gives the Net flow ( $\Phi$ ) (i.e., complete ranking). Overlapping of cones indicates incomparability.

Micro-hydro clearly emerges as the best-suited technology for India, followed by biomethanation in both the rankings. Biomass gasification is incomparable with Wind-PV in PROMETHEE I because biomass gasification performs better on few criteria while the other performs better on the other criteria. However, PROMETHEE II ranking places Biomass gasification slightly ahead of Wind-PV. Solar PV is ranked the lowest in the rankings. Its low  $\Phi$  scores could possibly be due to its good performance on factors such policy and regulations and technology



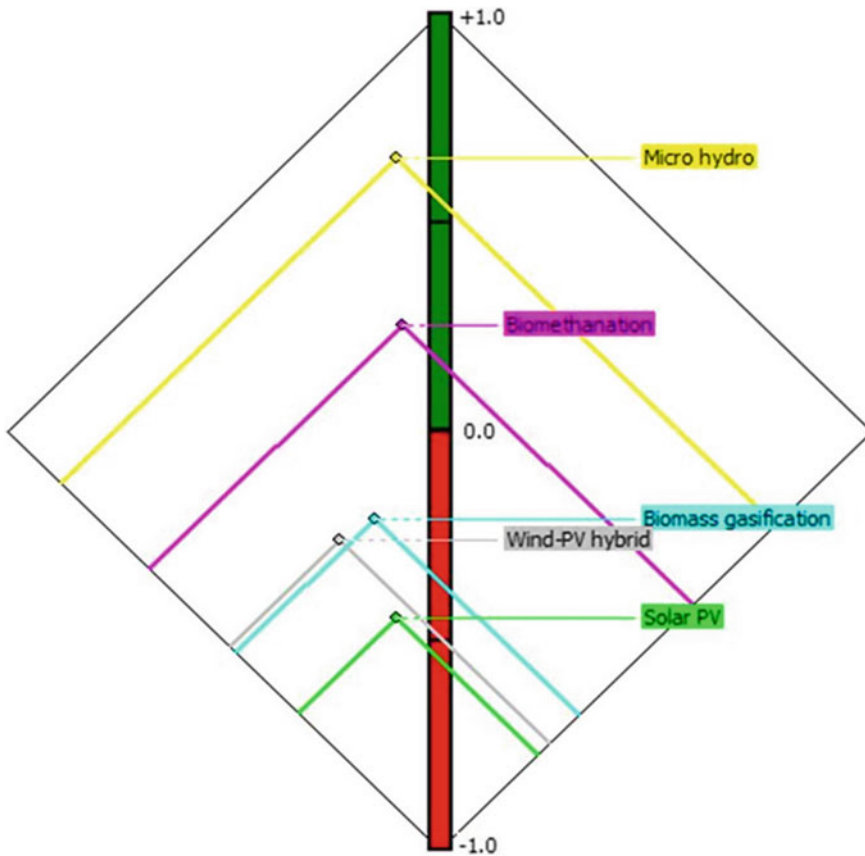


Fig. 5 PROMETHEE diamond-shaped rankings

maturity—factors that had low weightage. The reason for high Phi—scores could be due to its bad performance on factors such as initial capital cost, technology performance and social benefits. As this simulation indicates, RETs selection is not dominated by costs alone but is also greatly affected by technology maturity, technology performance, resource availability and social benefits.

The results suggest that in geographical regions with a sufficient resource, micro-hydro technology should be the most preferred solution for decentralised electrification. The two biomass technologies, despite their lower technical maturity and lack of policy support, are still worthy alternatives that cannot be overlooked, especially in countries such as India with abundant biomass availability.

Further sensitivity analysis is done to verify the stability of the rankings while changing the weightage of these criteria (see Figs. 7 and 8 for more details).

## 4.2 Visual Analysis of Results

GAIA is the descriptive companion method to PROMETHEE. GAIA starts from a multidimensional representation of the decision problem with as many dimensions as the number of criteria (ten in this study). A mathematical method called Principal Components Analysis is used to reduce the number of dimensions while minimising the loss of information. Using Visual PROMETHEE software, the multidimensional problem can be reduced to three dimensions— $U$ ,  $V$  and  $W$ . The GAIA plane (Fig. 6) is the two-dimensional representation on  $U$  and  $V$ .

On this  $U$ - $V$  plane, the RETs are represented by points, and the criteria are represented by axes. The position of each RET is related to its evaluation on the ten criteria such that RETs with similar profiles are closer to each other. For example, Solar PV and Wind-PV hybrid are very close to each other. Each criterion is represented by an axis drawn from the centre of the GAIA plane.

Criteria expressing similar preferences have axes that are close to each other, while conflicting criteria have axes that are pointing in opposite directions. For example technology performance and O&M costs are relatively close to each other. This suggests that it is possible to find solutions (RETs) that are good on both criteria simultaneously. Initial capital cost is pointing in almost opposite direction to supply chain availability. This suggests that it might not be possible to find an RET that has low initial capital cost and simultaneously has a good supply chain.

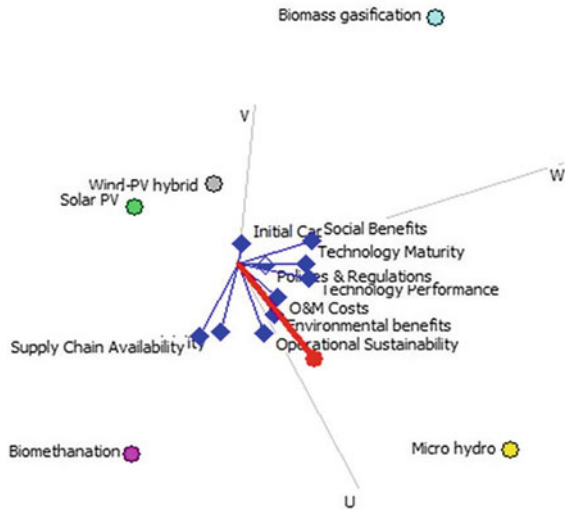
The relative positions of actions and criteria also reveal interesting information. The projection of an RET in the direction of an axis represents how good the RET performs on that criterion. This information is of course highly dependent on the quality of the GAIA plane represented by delta ( $\delta$ ). A ' $\delta$ ' value of greater than 70 % indicates that most of the information could be represented on the GAIA plane.

The Decision Axis (the thicker red axis) is the projection of the Decision Stick (i.e. the axis representing the weights of the criteria in the multidimensional space) onto the two-dimensional GAIA Plane. The orientation of the decision axis indicates which criteria are in agreement with the PROMETHEE rankings. The decision axis points to the direction of the best compromise solution (if one exists).

We can observe the axes are oriented in multiple directions, reflecting the varied dimensions to the decision problem. The technologies too are spread across in multiple directions, indicating their relative strengths and weaknesses. The biomass technologies, for instance, are located away from technology maturity thereby indicating their current low maturity levels (these are also located away from supply chain and policy axes, which is not surprising). Other than micro-hydro option, no other RET lies in the direction of the decision axis, thereby indicating their poor performance on one or more criteria. This suggests that in the current decision context, micro-hydro could be the only compromise solution in India.

Fig. 6 Global visual analysis

Zoom: 100%



### 4.3 Sensitivity Analysis

The inconsistency in stakeholder priorities could be attributed to the differences in expectations from each stakeholder group. For instance, while emissions reduction (environmental benefits) is a high priority for international donor agencies, other criteria such as the operational cost of the RET and employment generation for the local community are far more important priorities for private sponsors. The subjective nature of the value judgments, the conflicts observed in priorities for different stakeholder groups and the uncertainty in investment priorities warranted sensitivity analyses to be performed on the rankings. Weights of one or more criteria are increased while proportionately decreasing the weights of the rest. The change in the ranking is viewed in real time. Two types of sensitivity analyses are thus performed: (i) by varying stakeholder priorities and (ii) by varying investment priorities.

In accordance with the varied perspectives of different stakeholder groups, three different scenarios are created for the criteria in which maximum conflict was observed during criteria prioritization and the result is shown in Fig. 7:

#### Economic scenario

- Caters to the primary concerns of private sponsors.
- Initial capital cost and O&M cost criteria get highest priority.
- ICC and O&M together get 50 % weight.

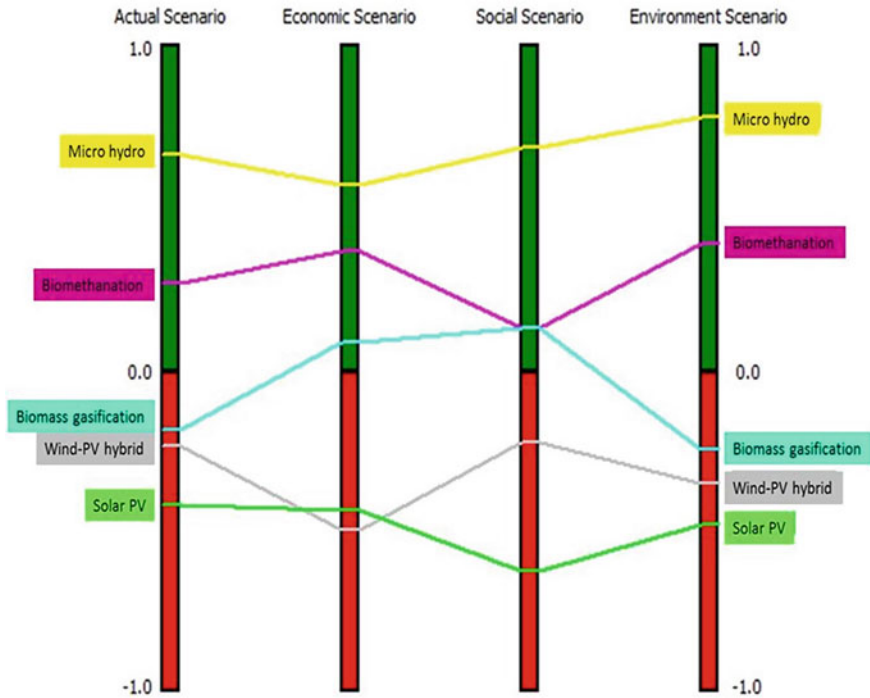


Fig. 7 PROMETHEE II ranking for varying stakeholder priorities

**Social scenario**

- Caters to the primary concerns of government and local citizens.
- Social benefits get 50 % weight.

**Environmental scenario**

- Caters to an increased awareness in protecting the environment.
- Environmental benefits get 50 % weight.

Sensitivity analyses by modifying the stakeholder priorities displayed very little change in the overall ranking (PROMETHEE II), which in turn revealed the stability of the initial ranking. Incomparability between biomass gasification and wind-PV hybrid was noticed in the environmental scenario. Also, biomass gasification was ranked close to the biomethanation technology in the social scenario. An interesting observation for the economic scenario was that the biomethanation technology was ranked very close to the dominant alternative. This suggests that it could be the best compromise solution in a ‘low cost’ scenario and in the absence of a sufficient hydro resource.

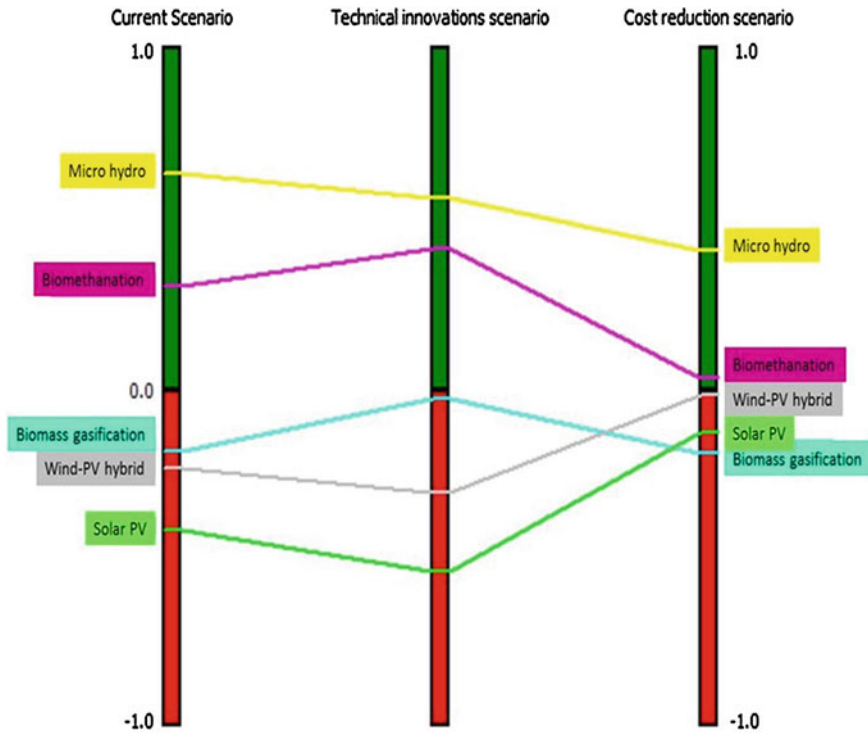


Fig. 8 PROMETHEE II ranking for varying investment priorities

Two exploratory scenarios are created to appreciate the probable areas in which investment would be necessary to promote the non-optimal technologies and to identify the technologies that could potentially develop into the best compromise solutions. The scenarios are developed in view of the scope for reduction in the prices of solar photovoltaic panels and in acknowledgement of the scope for technical improvement of the biomass technologies in developing countries. In either scenario, the performances of the technologies that received an impetus are modified to reflect the effect of the interventions. The result is shown in Fig. 8.

**Technical innovations scenario**

- Maximum investment in applied research to promote the least matured RETs;
- Extensive focus on technical innovations (For example, a high efficiency, standardised engine for biogas, simple anaerobic systems for specific substrates such as poultry waste, simple and efficient pelletizing machine for producing standardised fuel, among others) and supply chain improvement for biomethanation and biomass gasification (for example, involvement of forest officials in supplying sized biomass, employing women’s groups in cutting the fuelwood, pelletization, and so on).

- Technical maturity of both the biomass technologies was increased to equal the dominant RET.
- Their supply chain performance was changed to ‘good’.
- The modified PROMETHEE rankings thus obtained are shown in Fig. 8.

### **Cost reduction scenario**

- Extensive focus on cost reduction of the costliest RETs—Solar PV and Wind-PV hybrids.
- Initial capital cost of both reduced two fold.
- Their O&M cost reduced by half.

In the technical innovations scenario, with interventions to improve the least matured technologies, biomethanation ranked alongside micro-hydro. The score of biomass gasification too showed a significant improvement and is ranked the next best. It reveals that technical innovation alone is not a critical parameter for solar PV and Wind-PV hybrid for ranking the RETs. In the cost reduction scenario, the scores of both Solar PV and Wind-PV increased noticeably. However, neither of them scored as well as the dominant RET—micro-hydro. Biomass gasification is the least preferred option in this case.

## **5 Conclusions**

This chapter demonstrates the use of MCDA for selection and comparison of RETs for decentralised electrification in the context of a developing country. It also presents a comprehensive picture of the decision-making problems and assists the stake holders in India and South Asia to take a well-informed decision.

Analysis using PROMETHEE and GAIA revealed that micro-hydro is currently the best compromise renewable energy technology for decentralised electrification in India. The two biomass technologies—biomethanation and biomass gasification are ranked next. Low initial capital costs favour their choice but their low technical maturity level and poor supply chain availability are the major constraints affecting their adoption. Currently, biomethanation appears to be the next best compromise solution in geographical regions where sufficient hydro resource is unavailable. A dedicated investment in applied research and an extensive focus on localised innovation strategy can help boost the maturity of the biomass technologies and promote their accelerated diffusion in developing countries. Wind-PV hybrid and Solar PV are ranked the least. To improve these non-optimal technologies, there is a need for rapid decline in prices and the evolution of suitable financing and business models.

In the interim, new hybrid solutions and smart mini-grids can be adopted to effectively utilise the core strengths of each of the RETs in addition to maintaining diversity in supply options for decentralised electrification.

However, it merits mentioning the possible limitations of the study. The results of the study cannot be taken as sacrosanct, as the results largely correlate with input data obtained from field visits in India; the local needs, and resource availability. These constraints should be considered before interpreting the results to similar contexts in other developing countries. Therefore, it is difficult to generalise the findings of the study. A further generalisation requires information on a wider set of projects.

## Appendix

**Table A.1** Estimation of weights for criteria—an example

Criteria	1	2	3	4	5	6	7	8	9	10	Total	Weight
1. Initial capital costs	1	1	2	2	3	3	4	4	5	5	30	0.2206
2. Technology maturity		1	2	2	3	3	4	4	5	5	29	0.2132
3. O&M costs			1	1	2	2	3	3	4	4	20	0.1470
4. Technology performance				1	2	2	3	3	4	4	19	0.1397
5. Operational sustainability					1	1	2	2	3	3	12	0.0882
6. Social benefits						1	2	2	3	3	11	0.0808
7. Supply chain availability							1	1	2	2	6	0.0441
8. Resource availability and variability								1	2	2	5	0.0368
9. Policy and regulations									1	2	3	0.0220
10. Environmental benefits										1	1	0.0074
Total											136	

*Note* The method of calculating weights was adopted from a technical paper by Kohli et al. [29]

After placing the criteria into five categories of importance, they are compared pair-wise and values are given for each comparison as below:

- 1 if a criterion is being compared with itself.
- 1 if two criteria being compared belong to same category.
- 2 if first criterion is placed one category higher than second criterion.
- 3 if first criterion is placed two categories higher.
- 4 if first criterion is placed three categories higher.
- 5 if first criterion is placed four categories higher.

The weight coefficient for a particular criterion is obtained by dividing the individual score of that criterion by the total score for all the criteria.

**Table A.2** Survey for evaluating a technology on the identified criteria

Technology evaluated		Location	Date
<b>Mode of interview</b>			
Instructions:			
Please assign a score to the technology for each of the ten criteria below			
A score reflects how good/bad this technology performs for that particular criterion as compared to all other technology options available			
For cost criteria, please enter the actual costs noted at your site			
For criteria requiring qualitative scores, please circle the option that matches the most with the field conditions			
Selection criteria	Factors being assessed	Score	
Initial capital costs	Cost of equipment, civil works, battery storage, wiring and installation	_____	(Lakhs per kW)
O&M costs	Costs for fuel, labour, servicing and battery replacement (calculated pro rate)		(Rs. per kW per month)
Resource availability and variability	Availability of energy resource in the area/region	No resource availability	
	Variability of the resource throughout the year	Very low resource availability	
	Availability of land for installation and water for running the plant	Low resource, variable	
		Low resource, always available	
		Medium resource, variable	
		Medium resource, always available	
		High resource, variable	
		High resource, always available	
Technology maturity	Number of technology providers in the country	Very high resource availability, always available	
	Availability of standards	Technology barely use	
	Status of R&D	Very low maturity	
	Ease of use	Low maturity	
		Low-to-moderate maturity	
		Moderately mature	
		Moderate-to-high maturity	
		Highly mature but some areas for improvement	
		Highly mature with very minor concerns	
		Extremely mature technology	

(continued)



**Table A.2** (continued)

Selection criteria	Factors being assessed	Score
Technology performance	Ability to handle high-powered loads	Technology barely runs
		Very low performance
		Low performance
	Plant load factor	Low-to-moderate performance
		Moderate performance
		Moderate-to-high performance
		High performance, moderate downtime
		High performance, low downtime
		Excellent performance
		No supply chain exists
Supply chain availability	Availability of local manufacturing	Very low supply chain for few components
		Low supply chain for many components
	Local availability of spares and services	Low-to-moderate supply chain
		Moderate supply chain for key components
		Moderate supply chain for many components
		Good supply chain for most components
		Good supply chain for all components
		A reliable mature supply chain
		Unsustainable
		Very low sustainability
Operational sustainability	Availability of stable quality and quantity of fuel/feedstock throughout the lifetime of the project	Low sustainability on all criteria
	Availability of human resource for operation of the plant	Low sustainability on few criteria
		Moderately sustainable
	Scalability of the technology	High sustainability on few criteria
		High sustainability on all criteria
		Very high sustainability on all criteria
		Most sustainable

(continued)

Table A.2 (continued)

Selection criteria	Factors being assessed	Score
Policies and regulations	Policies favouring use of technology for decentralised electrification (includes subsidies available, scheme implemented in the past)	Detrimental policies Benign policies
	Environmental regulations	Negligibly favourable Slightly favourable Moderately favourable
	Policies promoting private enterprise	Favourable but many areas for improvement Mostly favourable Highly favourable
Environmental benefits	Reduction of CO <sub>2</sub> emissions (as compared to coal based power)	Extremely favourable policies No benefits to the environment Very negligible benefits
	Reduction in environmental degradation at the site	Low benefits on most factors Low benefits on some factors Moderate benefits on some factors Moderate benefits on most factors High benefits Very high benefits
Social benefits	Jobs to the local people in construction and operation of the plant	Extremely beneficial to environment No benefits to the society Very negligible benefits
	Increased income due to productive uses such as milling, de-husking	Low benefits on most factors considered Low benefits on some factors
	Involvement of women in the operation	Moderate benefits on some factors considered Moderate benefits on most factors
	Improvement in health, safety and education	High benefits Very high benefits Extremely beneficial to society

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