OASYS SOUTH ASIA Research Project

Working Paper Series

Working Paper 11

The quest for sustainable technology options for decentralised electrification using multi-criteria decision aids

Professor VVN Kishore and Dattakiran Jagu

TERI University, New Delhi

30 June 2011

Version: Final

Abstract

With over 1.3 billion people still lacking access to electricity, the task of supplying them reliable and affordable electricity is gargantuan. The government bodies and private investors in developing countries are obligated to invest judiciously by adopting the right technology solutions. With each of the renewable energy technologies varying immensely, choosing the best among them or ranking them is a huge challenge. This paper employs a multi-stakeholder approach using PROMETHEE, a multi-criteria decision aid for ranking the technology solutions for sustainable decentralized electrification. Further, a graphical descriptive analysis is applied to deduce the various conflicts and to reveal the necessary interventions.

The results show that micro hydro is currently the best compromise solution, followed by biomethanation. An extensive investment in technical innovations to boost the maturity of the biomass technologies and to reduce the costs of PV-based technologies is required before they can be adopted on a wider scale. New hybrids and smart mini-grids can be used in the interim for diversity in supply options.

Keywords: technology selection; technology ranking; multi-criteria decision aid; MCDA; PROMETHEE; sustainable energy; decentralized electrification

Please contact Prof. Subhes Bhattacharyya at subhesb@dmu.ac.uk for any clarifications/ issues on this working paper.

1.0 Introduction

The path of sustainable development is arduous, often compelling difficult decisions that could affect the most vulnerable. It has been widely recognised that lack of access to modern energy services acts as a severe impediment to human development **[1, 2].** Size of the population without electricity or commercial energy is one of the most crucial indicators to energy access **[3]**. With over 1.3 billion people —primarily in sub-Saharan Africa and developing Asia — still lacking access to electricity **[4]** and possibly an even larger number having only intermittent access to power, the task of supplying them reliable and affordable electricity is gargantuan. The resources that would be required to achieve this are equally enormous.

In a special early excerpt of the World Energy Outlook 2011 — "Energy use for All: Financing Access for the Poor" **[5]**, 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. About 90% of it is estimated for electrification alone. In a similar study, **Bazilian et al. [6]** have estimated the annual cost of universal access to electricity to be between $12 and $134 billion till 2030. These figures happen to be only a tiny fraction of the global investment required in energy infrastructure **[5].** But for the least electrified countries in the world, this additional investment is by no measure miniscule and is pivotal in liberating their billions from absolute poverty. This obligates the funding agencies, government bodies and private investors to invest judiciously by adopting the right solutions that target the most energy-poor while ensuring the long-term sustainability of these solutions.

A sustainable technology solution in the context of electrification is one that provides adequate electricity to improve the quality of human life by utilizing the local resources; can be manufactured locally; and can be operated within the constraints of the local eco-system. Although any form of electrification has the potential to provide economic growth, it is only with declining inequality, unemployment and poverty that a country can enjoy development **[8]**. Hence the technologies to be chosen for electrification should essentially be sustainable and also result in development, in other words, lead us on the path of sustainable development. Decentralized/distributed generation systems, due to their flexibility in size, fuel and technology choice, capability to produce reliable power **[9]** and ability to induce local autonomy, can rise to this challenge of sustainable development. Renewable energy technologies (RETs), potentially capable of powering the entire world **[10]** are also expected to a play a central role in moving the world onto a sustainable energy path **[4].** It is therefore imperative that the technology decision for energy access incorporates choosing among the RETs that are suitable for decentralized electrification.

The 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. Choosing the best solution(s) among them or ranking them is therefore a huge challenge.

With each technology producing varying quality of electricity output, comparing these diverse technologies is an even more daunting task. The decision problem gets further complicated if the perspectives — sometimes conflicting— of various stakeholders were to be considered. Problems of sustainable development such as this one are highly and are characterised by a high degree of conflict amongst multiple dimensions and multiple stakeholders. 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 **[11]**. This paper aims to employ a multi-stakeholder multi-criteria approach using MCDA for identifying the most effective technologies for sustainable decentralized electrification.

We further apply a graphical descriptive analysis to deduce the various conflicts involved in taking the decision. The graphical analysis also reveals the necessary interventions required for the wide-spread deployment of each of the technologies considered. Acceding to the argument that a single most-optimized solution might not exist for sustainable development problems **[11]**, this study limits itself to only identifying the best compromise technology solution(s). Although the results gained from the study relate to India, they can provide important insights for other developing countries in South Asia and sub-Saharan Africa.

The remainder of the paper is organized as follows: Section 2 contains a brief review of some of the previous studies for evaluating the RETs. Section 3 gives an introduction to the MCDA method PROMETHEE and the software D-Sight used for our analysis. Section 4 sequentially outlines the steps in the methodology used for ranking the RETs and presents the ranking obtained. A visual descriptive analysis of the decision problem and sensitivity analysis are further presented to create a better understanding of the issues and investment priorities. Section 6 concludes with recommendations for the non-best technologies.

2.0 Studies for comparison and selection of RETs

Studies for performance evaluation and selection among the various renewable energy options are abounding in academic literature. 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, exergy [**12, 13, 14, 15, 16, 17, 18, 19, 20]** ; (b) *Social, Economic and Environmental impacts* **[21, 22, 23, 24, 25, 26]** and (c) *Sustainability attributes* **[27, 28, 29, 30, 31]**. Techno-economic evaluations, that form the bulk of these studies, can help the DM in appreciating the technical and economic implications of a particular choice. However, due to their limited relevance to real-life conditions, they can seldom form the basis of an unequivocal decision.

Though social, economic and environmental impacts are irrefutably an integral part of sustainability assessment, studies based on these dimensions alone are found lacking crucial parameters such as the existence of a local eco-system for sustaining the RET installations in the long term. Hence, in spite of the significant overlap, the operational sustainability focussed studies can be demarcated as those that included the sustainability of the technology for supply of energy during and beyond the life time of the project.

A further classification of the evaluation studies can be made based on the approach used for analysing the energy options. Evaluations based on a single criterion such as cost of energy, are easier to analyze, but could be inadequate for decision-making. A slightly more complex approach involves optimization **[12, 25]** or break-even analysis **[18]** involving two or more criteria. Variations include those that seek the most optimal mix of RETs **[19]** when subject to input constraints. This approach nevertheless fails to consider multiple perspectives that are the norm for sustainable development decisions and the results could possibly remain unacceptable to many stakeholders. 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 **[30, 31]** that considers the aspirations and constraints of the local communities can result in a more credible solution **[32]** and can build their trust in decisions and political institutions **[33]**.

Whilst most initial studies were based on single-criterion approach focusing primarily on the techno-economic dimension, later studies employed multi-criteria approaches and started focussing on the social, economic, environmental and political dimensions as well. An emerging trend can also be observed towards sustainability-guided evaluations involving a multi-stakeholder or participatory approach and incorporating multiple criteria into the decision framework.

By employing numerous analysis techniques, most of the studies aimed to identify the most favourable technology or a single best-optimized solution within their decision context and to suggest policy recommendations for its choice. Kaya and Kahraman **[21]** for instance 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 mobilization and technology transfer of the identified technology **[26]** or to explore newer technical opportunities **[14].** 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. 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 analyze dissimilar information from multiple disciplines **[34].** They can provide the concepts and guidelines for structuring and modelling decision problems **[35]**, thereby aiding the decision making process in developing suitable criteria, in gaining acceptance of stakeholders and in creating new ideas for solutions **[11]**. With no right solution independent of the decision process **[36],** the decision taken can be only as legitimate as the underlying MCDA technique.

3.1 Selecting an MCDA technique

Numerous MCDA techniques and their classifications exist in literature. A detailed analysis of the various MCDA methods and their classification can be found in **[37, 38, 39, 40]** and other references.

Despite the large number of MCDA techniques, none is perfect **[41]** 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 suitable for sustainability issues by de Montis et al. **[42]** 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. For RET selection, Polatidis et al. **[43]** recommend that an analyst should necessarily consider the technique's treatment of the sustainability issue, modelling of the DM's 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 DMs. In our context, we chose to apply PROMETHEE — an outranking method, along with a multi-stakeholder approach in identifying the criteria for evaluation, prioritizing 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, using the GAIA 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.

3.2 PROMETHEE & GAIA

Preference Ranking Organization Method for Enrichment of Evaluations (PROMETHEE) **[44, 45, 46 and 47]** is an out-ranking technique typical of the European school of MCDA. An important advantage of PROMETHEE is that 'enriches' the raw performance scores of alternatives with a realistic interpretation of the DM's values on the differences in the scores for each criterion. After forming an evaluation matrix of performance of alternatives on all the criteria, the PROMETHEE process involves:

a. 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 **[46]** can be assigned by the DM, each representing a different perception of measurement scales for criteria.

b. Assigning weights to the criteria:

No specific guidelines exist for PROMETHEE for determining weights to the criteria. A simple method of calculating weights by pair-wise comparison of criteria used in **[48]** has been adopted in this paper.

c. Estimating the outranking degree of options:

Using the criteria weights and preference functions, a *multi-criteria preference degree* π (a, b) is computed as the weighted average of the preference functions P_j (a, b).

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

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

$$\Phi+(a) = \frac{1}{n-1}\sum_{x \in A} \pi(a, x)$$

$$\Phi-(a) = \frac{1}{n-1}\sum_{x \in A} \pi(x, a)$$

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

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

- PROMETHEE I — provides a partial ranking based on Φ+ and Φ- and permits incomparability between the alternatives
- PROMETHEE II — provides a complete ranking based on Φ 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 normalization 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 **[49, 50]**.

3.3 D-Sight software

D-Sight belongs to the third generation of decision support software based on the PROMETHEE-GAIA methodology. It allows structuring the decision problem intuitively by grouping similar criteria or similar alternatives. The alternatives could be scored either on numerical scales or user-defined qualitative scales. D-Sight's easy-to-use framework enables a faster decision making and its visual and collaborative tools allow a better interaction amongst the stakeholders. Tools available for sensitivity analysis allow discussing alternative scenarios more transparently, thereby increase the stakeholders' confidence in the solutions found. A desktop version of the software has been used for this paper.

4. Methodology

Research began by identifying the key stakeholders who would be involved in decentralized energy planning. Involving them is important to satisfy that the approach followed was rational, fair and transparent. Franco and Montibeller **[51]** 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. Participation of local citizens was initially believed to improve the quality of the decisions; but it was soon realized that their lack of knowledge regarding various crucial parameters of RETs prevented them from effective participation in meaningful discussions for prioritizing the criteria or for evaluating the technologies. However, informal discussions with them are helpful in capturing the aspirations of the local communities and therefore to develop suitable criteria that measure the ability of RETs to fulfil these aspirations.

The methodology given in **Figure 1** was used for our purpose to rank the RETs. This methodology is simple, transparent and efficient, while considering all the effective alternatives for resolving the problem. The sequential process makes it simple and easy to follow at each step and the recursive steps improve the quality of decision.

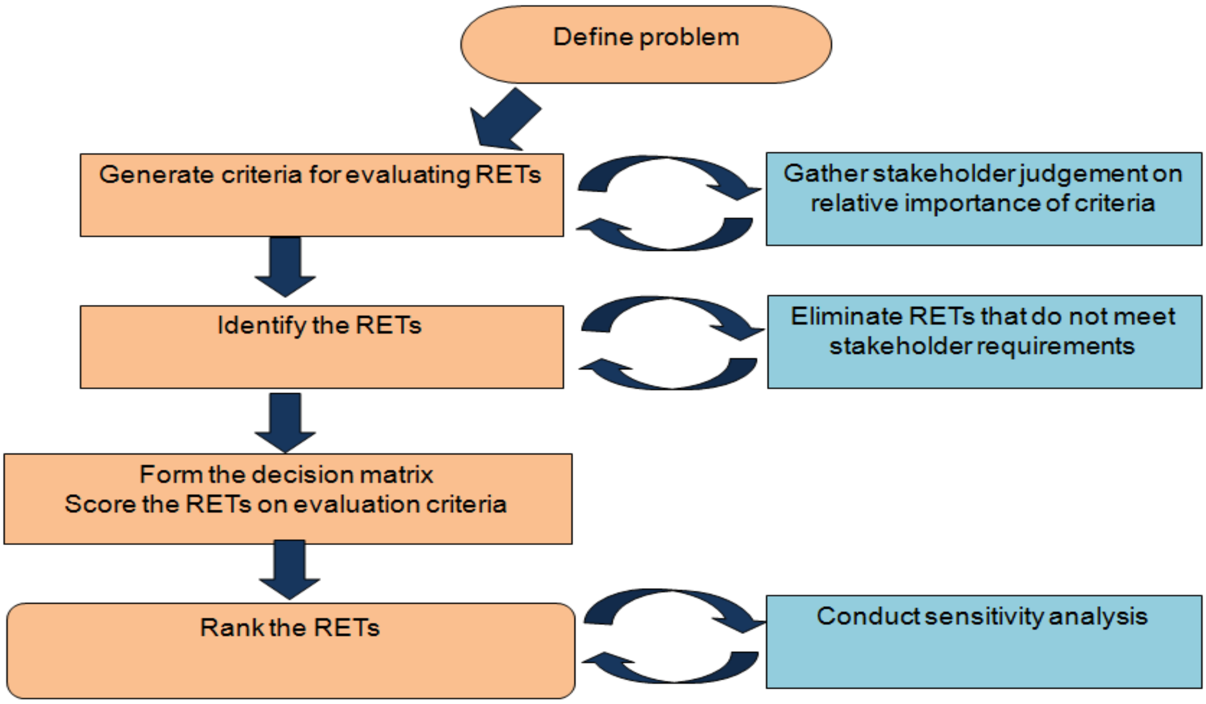

Figure 1: Ranking methodology

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.

4.1 Problem formulation

The first step is to represent the decision problem in the form of a decision value tree. A top-down approach was proposed for our study, driven by a single problem seeking a solution, 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. The principal objective of our study was *to identify the most sustainable and effective technology solution(s) for decentralized electrification*, while using a fair means of comparing and ranking them. And the scope of our study has been confined to those RETs that have at least one working, decentralized installation in India.

Next was to identify the various dimensions that need to be considered for taking a decision on a decentralized electrification project. Field visits are conducted to many such existing projects in India. Extensive discussions held with the project developers, technical experts and end consumers revealed the most important factors considered for setting up and operation of decentralized projects. These factors fell broadly into the following dimensions: Environmental, Social, Economic, Resource, Technical, Operational and Regulatory.

For structuring the decision value tree, Franco and Montibeller **[51]** suggest that the overall objective be broken down into smaller objectives that are essential, understandable, operational, non-redundant, concise and having preferential independence. Likewise, one objective was defined for each of the above dimensions.

4.2 Generation of evaluation criteria

For an analysis to lead to useful insights, Keeney and Gregory **[52**] define five desirable properties for the attributes: they should be unambiguous, comprehensive, direct, operational, and understandable. But data pertaining to sustainable development is rarely direct and can hardly be expressed in definite terms. Moreover, the concept of sustainability itself is evolving with time and with each increase in knowledge **[11]**. Trying to capture all the indicators of sustainability and generating a comprehensive set of criteria for its measurement can hence turn into a futile exercise. A fine balance was therefore necessary to restrict our analysis to a finite set of criteria while simultaneously ensuring most of the constraints for technology decision are addressed and adequate provisions exist for capturing poorly defined subjective inputs. This required that where inputs cannot be easily measured, new criteria be constructed and qualitative scales be defined for them to effectively capture the stakeholder value judgements.

A review of sustainability assessment studies for RETs revealed the most widely used sustainability indicators. In their review of MCDA techniques for sustainable energy decision-making, **Wang et al. [53]** identified at least 25 criteria, broadly categorized into Technical, Economic, Environmental and Social indicators. For studies on rural electrification, **Ilskog [54]** proposed 39 sustainability indicators, grouped under five dimensions: Technical, Economic, Social/ethical, Environmental and Institutional sustainability. **Cornelia and Hennings [27]** compiled 86 sustainability criteria, arranged in the form of a value tree to evaluate four different explorative scenarios of decentralized electricity generation. The goal of sustainability was differentiated on three levels, with environmental protection, health protection, security of supply, economic aspects and social aspects defined in the first level.

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 green house gas (GHG) emissions and land use was the oft-used environmental indicators. Other critical indicators included the availability of the renewable resource and availability of human resource for operating and servicing the technology. A pervasive inter-dependence could be observed amongst most of these indicators.

Informal discussions with local citizens further revealed that factors such 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 1**. The criteria are chosen so as to incorporate all the important dimensions of the decision while ensuring the relative independence of each criterion.

Table 1: Evaluation criteria

Criteria	Scale	Factors assessed
Environmental benefits	Qualitative	Reduction in COx 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 &	Qualitative	Availability of energy resource in the specific

variability		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
Operation & 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
Supply chain availability	Qualitative	Availability of local manufacturing, Local availability 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 & Regulations	Qualitative	Policies favouring decentralized electrification, Environmental regulations, Policies for promoting private enterprise

4.3 Prioritization of evaluation criteria

Once the evaluation criteria are identified, the next step was to prioritize 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.

Interviews with key stakeholders

Representatives from each of the identified key stakeholder groups, having experience with at least one RE technology but aware of all the other technologies are randomly chosen across multiple geographic locations in India. Ten such key stakeholders are interviewed personally or over the phone with a written survey questionnaire to elicit their opinion on the relative importance of the criteria. Semi-structured interviews are conducted in a conversational format

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 that the stakeholder could enter the priorities on a scale of 1 (highest priority) to 10 (least priority) or could categorize the criteria into five categories of importance — Very high, High, Medium, Low, Very low.

Analysis of survey results for prioritization 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 the stakeholders. This high variation in stakeholder priorities — particularly of criteria such as Initial capital costs, Social benefits and Environmental benefits clearly depicts the conflicting views among the various groups of stakeholders and the subjective nature of their opinions.

After each survey, weights are calculated for each criterion using a method adopted from **[55]**. An example for calculation of weights is provided in **Appendix I**. 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 are averaged.

4.4 Identification of RETs

For our study, we employed an approach of multiple rounds of discussions and brain-storming with multiple stakeholders in eliciting as many alternatives as possible. The focus of the discussions was on the primary objective to be achieved. The key stakeholders pointed out that few of the RETs could be combined in some instances. But having too many choices may paradoxically lead to a less satisfactory decision **[56]**. Hence, limiting to a finite number of RETs, we chose to include only one hybrid: Small wind turbine – Solar PV hybrid in our study. Options such as geothermal technologies, which are not relevant to South Asia and options such as Fuel Cells which are still in their nascent stage of development and currently extremely expensive are removed from further analysis. The RETs identified for our study are mentioned in **Figure 2**.

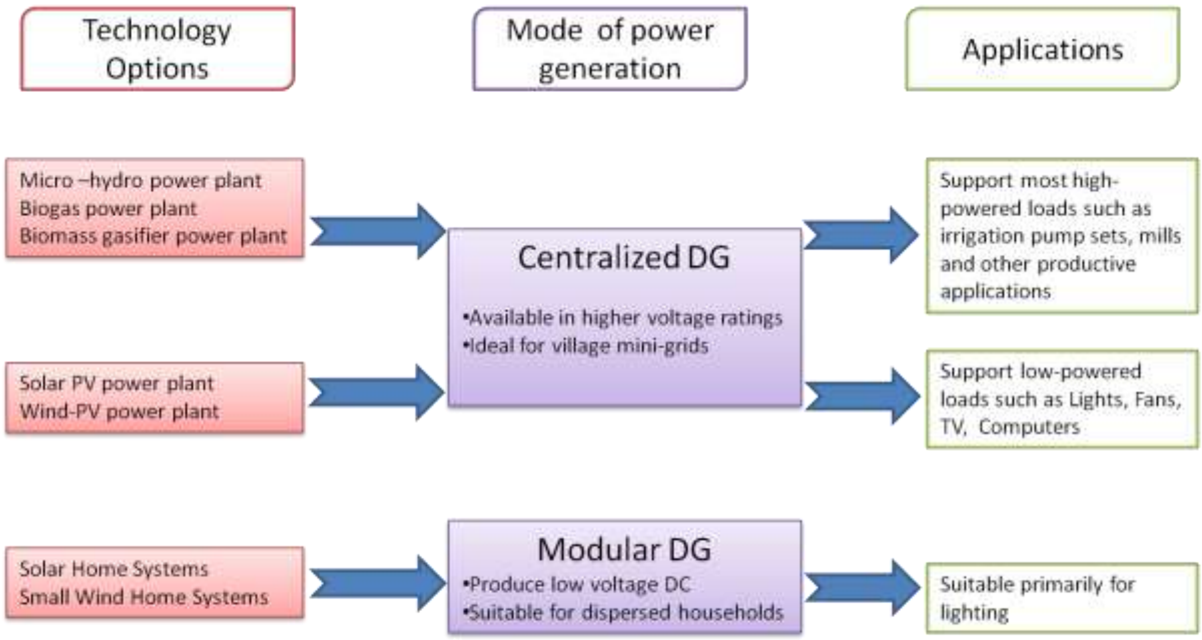

Figure 2: RET options identified

Solar home systems and Small wind home systems, though ideal for individual homes and battery charging stations, are found to be unsuitable for mini-grids. Due to their inherent limitations, 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.

4.5 Formation of a decision matrix and scoring of RETs

Once the alternatives are determined, the next step was to evaluate the alternatives for the criteria defined. Data was obtained by field visits to decentralized installations across six states/provinces spread across India. Various stakeholders such as technology experts, project developers and NGOs are asked to rate the particular technology in which they had previous experience/expertise. Where criteria could not be quantitatively measured, suitable qualitative scales with nine levels of measurement are constructed.

ESMAP **[57]**, in 2007, had estimated the capital and working costs for most of the renewable technologies over a 10 year period. Though this would not give an accurate measure, it would definitely be useful to estimate the approximate costs. Costs obtained from field visits are corroborated with the ESMAP study to eliminate any unrealistic cost estimates that were reported during the field visits. The decision matrix thus constructed is given in **Table 2**.

Table 2: Decision matrix

	Weight (%)	Units/ Scale	Solar PV	Micro hydro	Biomethanation	Biomass gasification	Wind-PV hybrid
Resource availability & variability	**14.85**	**(1 to 9)**	**6**	**8**	**8**	**5**	**7**
Environmental benefits	**13.11**	**(1 to 9)**	**8**	**9**	**9**	**9**	**9**
Initial Capital Cost	**12.85**	**$/kW**	**5555**	**4629**	**2000**	**1555**	**5000**
Technology performance	**11.87**	**(1 to 9)**	**4**	**8**	**8**	**7**	**5**
Social benefits	**10.24**	**(1 to 9)**	**5**	**9**	**7**	**8**	**5**
O & M Costs	**9.93**	**$/kW /month**	**46.29**	**3.40**	**22.22**	**24.15**	**44.44**
Technology maturity	**9.49**	**(1 to 9)**	**8**	**8**	**4**	**5**	**7**
Operational sustainability	**8.72**	**(1 to 9)**	**7**	**9**	**7**	**5**	**6**
Supply chain availability	**4.91**	**(1 to 9)**	**7**	**5**	**6**	**2**	**6**
Policies & Regulations	**3.96**	**(1 to 9)**	**8**	**7**	**3**	**2**	**7**

Source: Field visits

Note: A conversion of 1 USD = 45 INR was assumed

4.5 Ranking of the RETs

With the decision matrix and the criteria weights as inputs, PROMETHEE analysis is performed using D-Sight software. Suitable preference functions 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. The partial (PROMETHEE I) and complete (PROMETHEE II) rankings thus obtained are given in **Figure 3**.

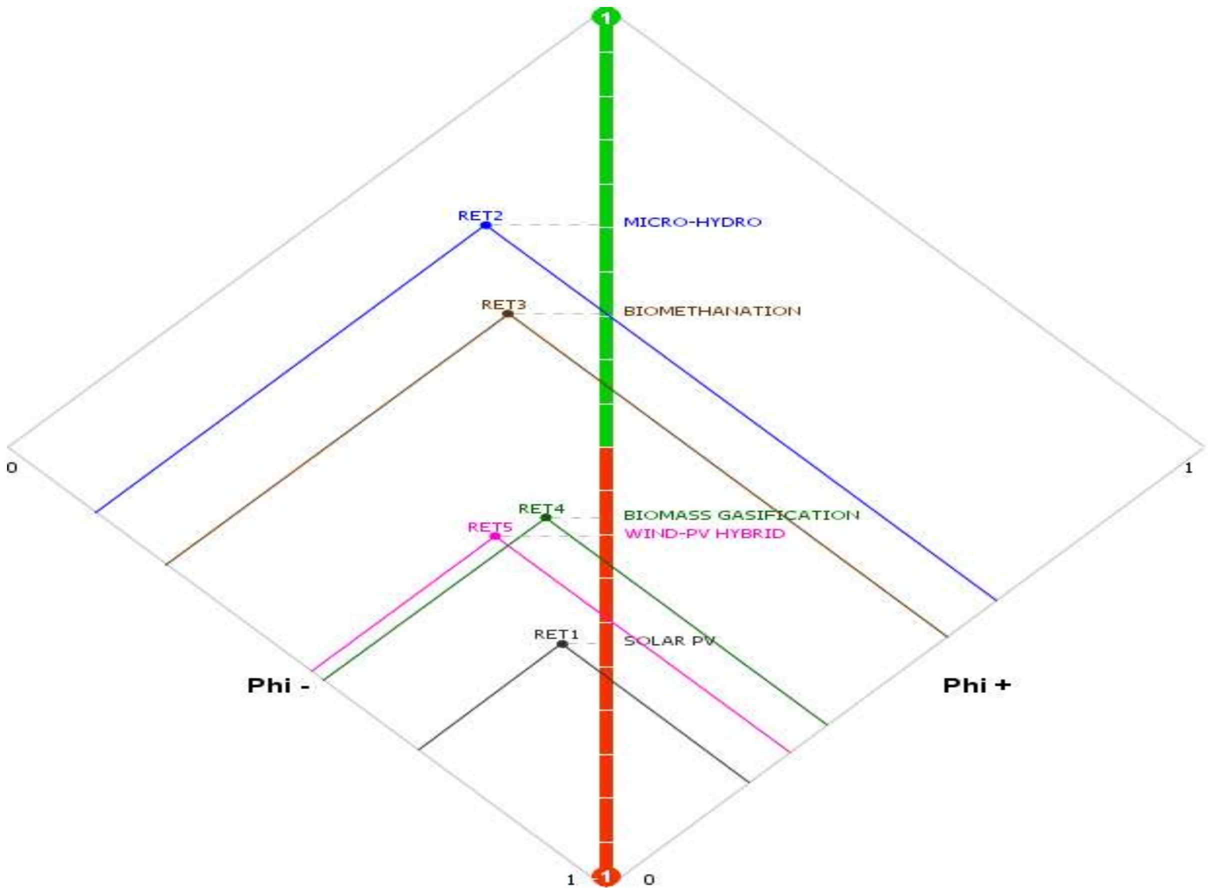

Figure 3: PROMETHEE I and PROMETHEE II rankings

PROMETHEE I provides a partial ranking based on the positive (Φ+) and negative (Φ-) flows of the alternatives. And PROMETHEE II provides a complete ranking based on the net flow (Φ). D-Sight software allows the simultaneous viewing of both these rankings using a diamond-shaped representation. Inside the PROMETHEE Diamond, the RETs are placed based on their relative strengths (Φ+) and weaknesses (Φ-). The 2 axes are angled such that each RET is a cone. The intersection of the two flows gives the partial ranking and the projection of the meeting on a vertical axis gives the Net flow (Φ) (i.e., complete ranking). Overlapping of cones indicates incomparability.

Micro-hydro clearly emerges as the top-ranked technology, followed by Biomethanation. Biomass gasification and Wind-PV are incomparable in PROMETHEE I, while PROMETHEE II places Biomass gasification slightly ahead of Wind-PV. Solar-PV is ranked the lowest in both the rankings.

4.6 Visual analysis of results

A Global visual analysis diagram using D-Sight (**Figure 4**) gives a multidimensional depiction of the different RETs (as dots) and criteria (as axes) on the GAIA plane. The longer an axis is in the GAIA plane, the more priority it has. An RET lying in the direction of an axis indicates its better performance for that criterion. Axes in the same direction indicate correlation between the corresponding criteria and axes in opposite directions indicate conflicting criteria. The 'pi' axis represents the direction of the best compromise solution. The further an RET's projection goes on the 'pi' axis, the better it is. A delta (δ) value of greater than 70% indicates that most of the data could be represented in the GAIA plane.

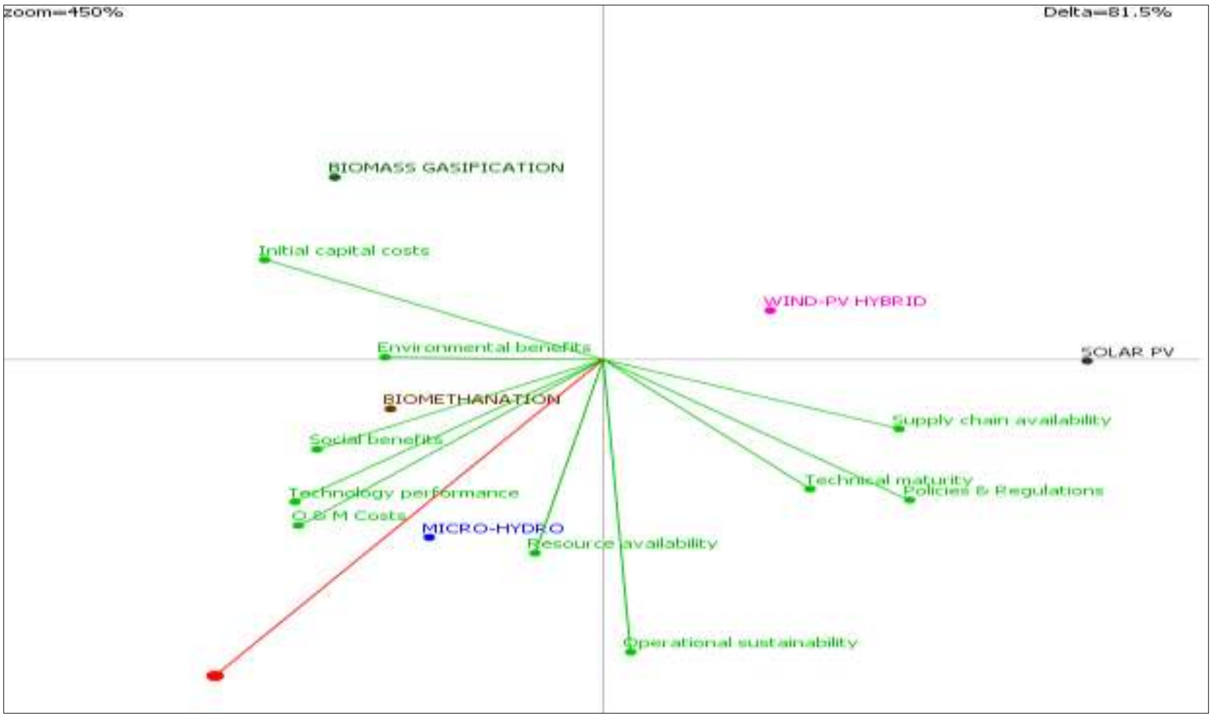

Figure 4: Global visual analysis

In **Figure 4**, each axis points in a different direction, reflecting the varied dimensions to the decision problem. The technologies too are spread across in multiple directions. The biomass technologies, for instance, are located away from technology maturity thereby indicating their current low maturity levels. On the other extreme, Solar-PV and Wind-PV hybrids are located away from initial capital cost, thus indicating their high initial cost. Other than micro-hydro option, no other RET lies in the direction of the 'pi' axis, thereby indicating their poor performance on one or more criteria. This suggests that in the current decision context, barring micro-hydro, no other best compromise solution seems to exist.

4.7 Sensitivity analysis

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. The 'walking weights' feature of D-Sight allows weights of a particular criterion to be increased while proportionately decreasing the weights of the rest. The change in the ranking could be viewed in real time. Using this feature, two types of sensitivity analyses are performed: (i) By varying stakeholder priorities, (ii) By varying investment priorities.

Varying stakeholder priorities

In accordance to the varied perspectives of the different stakeholder groups, three different scenarios are created for the criteria in which maximum conflict was observed during criteria prioritization:

A) 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

PROMETHEE-I Ranking:

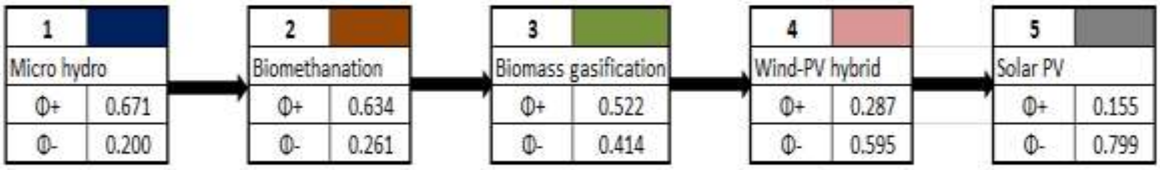

Figure 5: Ranking for Economic scenario

B) Social scenario

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

PROMETHEE-I Ranking:

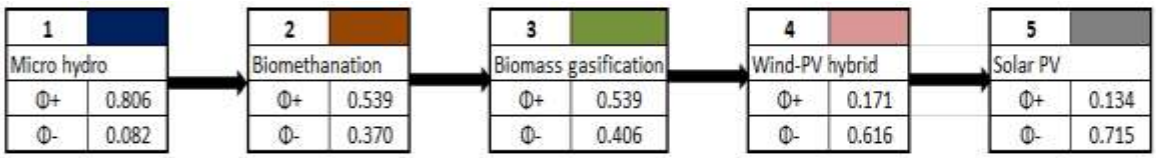

Figure 6: Ranking for Social scenario

C) Environmental scenario

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

PROMETHEE-I Ranking:

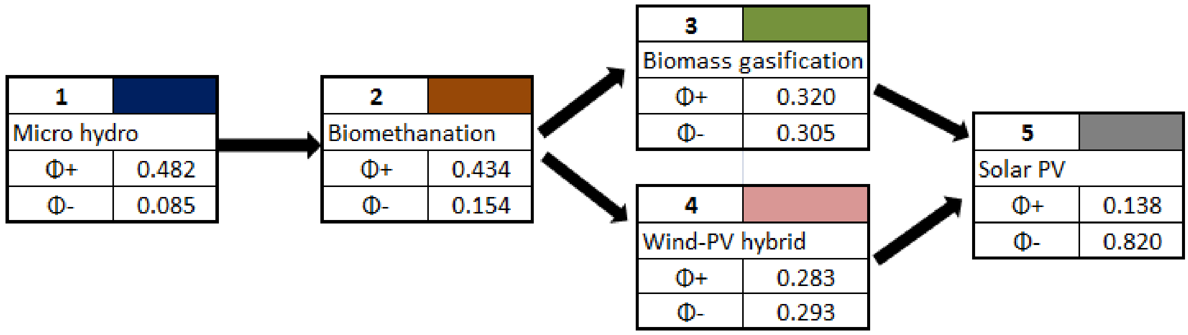

Figure 7: Ranking for Environmental scenario

Sensitivity analyses by modifying the stakeholder priorities displayed no 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. 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 costs’ scenario and in the absence of a sufficient hydro resource.

Varying investment priorities

Two exploratory scenarios are created to appreciate the probable areas in which investment would be necessary to promote the non-best 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.

D) Technical innovations scenario

- Maximum investment in applied research to promote the least matured RETs
- Extensive focus on technical innovations and supply chain improvement for biomethanation and biomass gasification
- Technical maturity of both the biomass technologies was increased to equal the dominant RET
- Their supply chain performance was changed to ‘good’

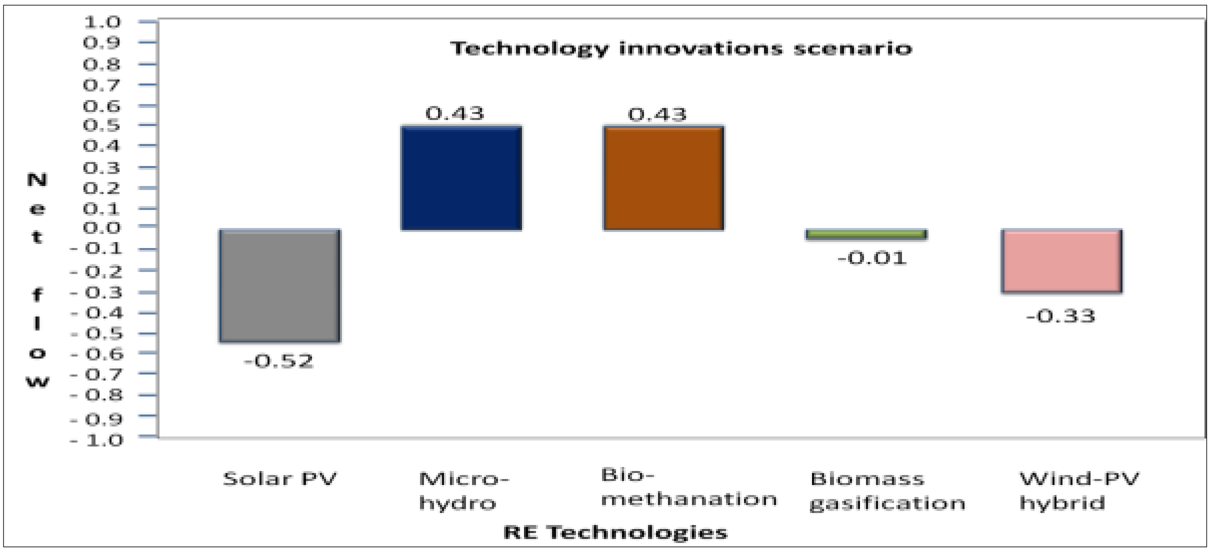

Figure 8: Technical innovations scenario

E) Cost reduction scenario

- Extensive focus on cost reduction of the costliest RETs – Solar PV and Wind-PV hybrids
- Initial capital cost of both reduced by 200%
- Their O&M cost reduced by 100%

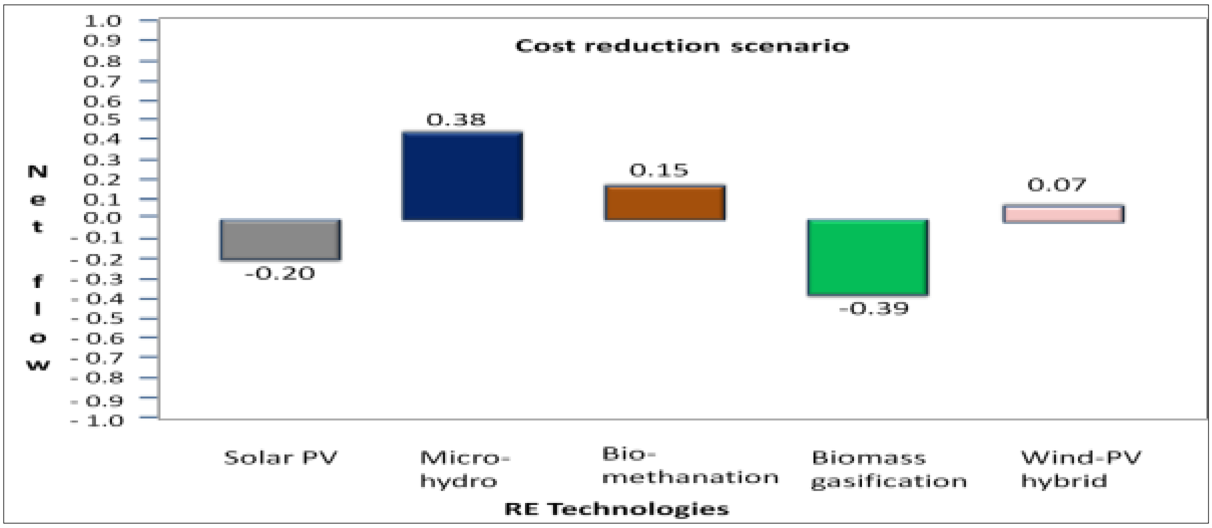

Figure 9: Cost reduction scenario

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. And 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

The primary aim of this study is not to identify the best technology solution for decentralized electrification. Rather, the intention is to present to the key stakeholders in developing countries, a comprehensive picture of the decision problem and assist them in taking a well-informed decision. The results relate to input data obtained from field visits in India; the local resource availability should be considered before interpreting the results to similar contexts in other countries.

Analysis using PROMETHEE and GAIA revealed that micro hydro is currently the best-compromise technology for decentralized electrification. 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. With a rapid decline in prices and the evolution of suitable financing and business models, these technologies could play a vital role in the future.

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

References

[1] Ramani, K.V., Energy for sustainable development: Challenges for Asia and the Pacific and lessons from UNDP projects in the region, (2004), UNDP.

[2] GNESD, Reaching the Millennium Development Goals and Beyond: Access to Modern Forms of Energy as a Prerequisite (2007).

[3] IAEA, Energy indicators for sustainable development: Guidelines and Methologies (2005).

[4] IEA, World Energy Outlook (2010).

[5] IEA, Energy for all: Financing access for the poor (2011).

[6] M. Bazilian, P. Nussbaumer, E. Haites, M. Levi, M. Howells and K. K. Yumkella, Understanding the Scale of Investment for Universal Energy Access, *Geopolitics of Energy*, 32 (2010), pp. 19-40.

[7] *Practical Action, Energy Poverty: The hidden energy crisis (2009),* Available at: http://practicalaction.org/docs/advocacy/energy_poverty_hidden_crisis.pdf

[8] D. Seers, The meaning of development, *International Development Review*, 11 (1969), pp. 2-6.

[9] IEA, Distributed generation in liberalised electricity markets, International Energy Agency (OECD/IEA), Paris (2002).

[10] 'Renewables can power the world, says IPCC', *The Hindu*, 12 May, viewed 12 May 2011, Available at: http://www.hindu.com/seta/2011/05/12/stories/2011051255071700.htm

[11] I. Omann, Multi-criteria decision aid as an approach for sustainable development analysis and implementation, Ph.D. Thesis, University of Graz, (2004).

[12] M. M. Mahmoud and I. H. Ibrik, Techno-economic feasibility of energy supply of remote villages in Palestine by PV-systems, diesel generators and electric grid, *Renewable and Sustainable Energy Reviews*, 10 (2006), pp.128-138.

[13] K. Q. Nguyen, Alternatives to grid extension for rural electrification: Decentralized renewable energy technologies in Vietnam, *Energy Policy*, 35 (2007), pp. 2579-2589.

[14] A. Hepbasli, A key review on exergetic analysis and assessment of renewable energy resources for a sustainable future, *Renewable and Sustainable Energy Reviews*, 12 (2008), pp. 593-661.

[15] F. Chen, S. Lu, K. Tseng, S. Lee and E. Wang, Assessment of renewable energy reserves in Taiwan, *Renewable and Sustainable Energy Reviews*, 14 (2010), pp. 2511-2528.

[16] P. Purohit, Financial evaluation of renewable energy technologies for irrigation water pumping in India, *Energy Policy*, 35 (2007), pp. 3134-3144.

[17] D. Thiam, Renewable decentralized in developing countries: Appraisal from microgrids project in Senegal, *Renewable Energy*, 35 (2010), pp. 1615-1623.

[18] S. Munuswamy, K. Nakamura and A. Katta, Comparing the cost of electricity sourced from a fuel cell-based renewable energy system and the national grid to electrify a rural health centre in India: A case study, *Renewable Energy*, 36 (2011), pp. 2978-2983.

[19] A.B. Kanase-Patil, R.P. Saini and M.P. Sharma, Integrated renewable energy systems for off grid rural electrification of remote area, *Renewable Energy*, 35 (2010), pp. 1342-1349.

[20] M.R. Nouni, S.C. Mullick and T.C. Kandpal, Providing electricity access to remote areas in India: Niche areas for decentralized electricity supply, *Renewable Energy*, 34 (2009), pp. 430-434.

[21] T. Kaya and C. Kahraman, Multicriteria renewable energy planning using an integrated fuzzy VIKOR & AHP methodology: The case of Istanbul, *Energy*, 35 (2010), pp. 2517-2527.

[22] R. Ramanathan and L.S. Ganesh, A multi-objective evaluation of decentralized electricity generation options available to urban households, *Energy Conversion and Management*, 35 (1994), pp. 661-670.

[23] T. Catalina, J. Virgone and E. Blanco, Multi-source energy systems analysis using a multi-criteria decision aid methodology, *Renewable Energy*, 36 (2011), pp. 2245-2252.

[24] M. Beccali, M. Cellura and M. Mistretta, Decision-making in energy planning. Application of the Electre method at regional level for the diffusion of renewable energy, *Renewable Energy*, 28 (2003), pp. 2063-2087.

[25] Varun, Ravi Prakash and I.K. Bhat, A figure of merit for evaluating sustainability of renewable energy systems, *Renewable and Sustainable Energy Reviews*, 14 (2010), pp. 1640-1643.

[26] H. Doukas, V. Marinakis, C. Karakosta and J. Psarras, Promoting renewables in the energy sector of Tajikistan, *Renewable Energy*, 39 (2012), pp. 411-418.

[27] C. R. Karger and W. Hennings, Sustainability evaluation of decentralized electricity generation, *Renewable and Sustainable Energy Reviews*, 13 (2009), pp. 583-593.

[28] S. Yi, H. Sin and E. Heo, Selecting sustainable renewable energy source for energy assistance to North Korea, *Renewable and Sustainable Energy Reviews*, 15 (2011), pp. 554-563.

[29] M. Amer and T. U. Daim, Selection of renewable energy technologies for a developing county: A case of Pakistan, *Energy for Sustainable Development*, 15 (2011), pp. 420-435.

[30] J. A. Cherni, I. Dyner, F. Henao, P. Jaramillo, R. Smith and R. O. Font, Energy supply for sustainable rural livelihoods. A multi-criteria decision-support system, *Energy Policy*, 35 (2007), pp. 1493-1504.

[31] H. Polatidis and D. Haralambopoulos, Local Renewable Energy Planning: A Participatory Multi-Criteria Approach, *Energy Sources*, 26 (2004), pp. 1253-1264.

[32] S. C. Bhattacharyya, Review of alternative methodologies for analysing off-grid electricity supply, *Renewable and Sustainable Energy Reviews* (2011), DOI: 10.1016/j.rser.2011.08.033

[33] Rowe, G. and Frewer, L. J. (2000). Public Participation Methods: A Framework for evaluation, *Science, Technology and Human* Values, 25 (1), 3-29.

[34] I. Linkov, A. Varghese, S. Jamil, T. P. Seager, G. Kiker and T. Bridges, Multi-criteria decision analysis: A framework for structuring remedial decisions at contaminated sites, in: I. Linkov, A. B. Ramadan (Eds.), Comparative Risk Assessment and Environmental Decision Making, Kluwer Academic Publishers, Dordrecht, 2004, pp. 15-49.

[35] B. Roy, D. Vanderpotten, The European School of MCDA: Emergence, Basic Features and Current Works. *Journal of Multi-Criteria Decision Analysis,* 5 (1996), pp.22-38.

[36] B. Roy, *Multicriteria Methodology for Decision Aiding*. Kluwer Academic Publishers, Dordrecht, 1996.

[37] J. Figueira, S. Greco and M. Ehrgott, *Multiple Criteria Decision Analysis: State of the Art Surveys*, Springer Verlag, Boston, Dordrecht, London, 2005.

[38] E. Triantaphyllou, Multi-Criteria Decision Making Methods: A Comparative Study, in: P. M. Pardalos and D. Hearn (Eds.), Appplied Optimization. Dordrecht, Boston, London: Kluwer Academic Publishers, 2000.

[39] V. Belton, T. J. Stewart, *Multiple Criteria Decision Analysis - An integrated approach*, Kluwer Academic Publishers, Boston, MA, 2002.

[40] A. Guitouni and J. Martel, Tentative guidelines to help choosing an appropriate MCDA method, *European Journal of Operational Research*, 109 (1998), pp.501-521.

[41] J. Martel, Multicriterion Decision Aid: Methods and Applications (undated), Accessed on 02 Dec, 2011, Available at: http://www.cors.ca/bulletin/v33n1_1e.pdf

[42] A. De Montis, P. De Toro, B. Droste-Franke, I. Omann and S. Stagl, Criteria for quality assessment of MCDA methods in: M. Getzner, C. Spash, S. Stagl, (Eds) , *Alternatives for environmental evaluation*, Routledge, London (2005), pp. 99–133.

[43] H. Polatidis, D. A. Haralambopoulos, G. Munda and R. Vreeker, Selecting an Appropriate Multi-Criteria Decision Analysis Technique for Renewable Energy Planning, *Energy Sources*, Part B, vol. 1 (2006), pp. 181-193.

[44] J. P. BRANS, L'ingéniérie de la décision.Elaboration d'instruments d'aide à la décision. Méthode PROMETHEE, Université Laval, Québec, Canada, 1982.

[45] J. P. BRANS and P. VINCKE, A preference ranking organization method: The PROMETHEE method for MCDM', Management Science, 31, 6, (1985), pp.647-656.

[46] J. P. BRANS, B. MARESCHAL and P. VINCKE, How to select and how to rank projects : The PROMETHEE method for MCDM, *EJOR*, 24, (1986), pp.228-238.

[47] J. P. BRANS, B. MARESCHAL, PROMCALC & GAIA : A new decision support system for multicriteria decision aid, *Decision Support Systems*, 12, (1994), pp.297-310.

[48] S. Kohli, P. Raman, VVN. Kishore, Evaluation of various fuels for gasification, in: Energy options for the 90's, *Solar Energy Society of India*, Tata McGraw Hill, New Delhi, (1988), pp. 508–14.

[49] J. P. Brans, B. Mareschal, How to Decide with PROMETHEE, Systems Science, (2000), pp. 1-5, Available at: http://scholar.google.com/scholar?hl=en&btnG=Search&q=intitle:How+to+Decide+with+PROMETHEE#0

[50] B. Mareschal, Y. V. Smet, New Developments of the PROMETHEE & GAIA MCDA Methods, Available at: http://homepages.ulb.ac.be/~bmaresc/PromGaia/pptSanDiego.html

[51] L. A. Franco. and G. Montebeller, *Problem Structuring for Multi-Criteria Decision Analysis Interventions,* The London School of Economics and Political Science, London, 2009.

[52] R.L. Keeney and R.S. Gregory, Selecting Attributes to Measure the Achievement of Objectives, *Operations Research*, 53 (2005), pp. 1-11.

[53] J.-J. Wang, Y.-Y. Jing, C.-F. Zhang and J.-H. Zhao, Review on multi-criteria decision analysis aid in sustainable energy decision-making, *Renewable Sustainable Energy Rev*, **13** (2009), pp. 2263–2278.

[54] E. Ilskog, Indicators for assessment of rural electrification—An approach for the comparison of apples and pears, *Energy Policy*, 36 (2008), pp. 2665-2673.

[55] S. Kohli, P. Raman and VVN. Kishore, Evaluation of various fuels for gasification, in: Energy options for the 90's, *Solar Energy Society of India*, Tata McGraw Hill, New Delhi, 1988, pp. 508–514.

[56] S. S. Iyengar and M. R. Lepper, When Choice is Demotivating: Can One Desire Too Much of a Good Thing?, *Journal of Personality and Social Psychology*, 79 (2000), pp. 995-1006.

[57] Energy Sector Management Assistance Program (ESMAP), Technical and Economic Assessment of Off-grid, Mini-grid and Grid Electrification Technologies (2007). Technical Paper.

Appendices

Appendix I. 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 & variability								1	2	2	5	0.0368
9. Policy & 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. [55]. 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.

Acknowledgement

The activities reported in this report are funded by an EPSRC/ DfID research grant (EP/G063826/2) from the RCUK Energy Programme. The Energy Programme is a RCUK cross-council initiative led by EPSRC and contributed to by ESRC, NERC, BBSRC and STFC.

Disclaimer

The views expressed in this report are those of the authors and do not necessarily represent the views of the institutions they are affiliated to or that of the funding agencies.

OASYS South Asia project

The Off-grid Access Systems for South Asia (or OASYS South Asia) is a research project funded by the Engineering and Physical Sciences Research Council of UK and the Department for International Development, UK. This research is investigating off-grid electrification in South Asia from a multi-dimensional perspective, considering techno-economic, governance, socio-political and environmental dimensions. A consortium of universities and research institutes led by De Montfort University (originally by University of Dundee until end of August 2012) is carrying out this research. The partner teams include Edinburgh Napier University, University of Manchester, the Energy and Resources Institute (TERI) and TERI University (India).

The project has carried out a detailed review of status of off-grid electrification in the region and around the world. It has also considered the financial challenges, participatory models and governance issues. Based on these, an edited book titled "Rural Electrification through Decentralised Off-grid Systems in Developing Countries" was published in 2013 (Springer-Verlag, UK). As opposed to individual systems for off-grid electrification, such as solar home systems, the research under this project is focusing on enabling income generating activities through electrification and accordingly, investing decentralised mini-grids as a solution. Various local level solutions for the region have been looked into, including husk-based power, micro-hydro, solar PV-based mini-grids and hybrid systems. The project is also carrying out demonstration projects using alternative business models (community-based, private led and local government led) and technologies to develop a better understanding of the challenges. It is also looking at replication and scale-up challenges and options and will provide policy recommendations based on the research.

More details about the project and its outputs can be obtained from www.oasyssouthasia.dmu.ac.uk or by contacting the principal investigator Prof. Subhes Bhattacharyya (subhesb@dmu.ac.uk).

OASYS South Asia Project
Institute of Energy and Sustainable Development,
De Montfort University,
The Gateway, Leicester LE1 9BH, UK

Tel: 44(0) 116 257 7975