Alternative Energy Options for India— A Multi-criteria Decision Analysis to Rank Energy Alternatives using Analytic Hierarchy Process and Fuzzy Logic with an Emphasis to Distributed Generation

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ABSTRACT

Several studies have been performed in last many years as to which type of energy source would be suitable for extending energy access for remote rural areas. Energy planning using multi-criteria analysis has attracted the attention of decision makers for a long time. Multi-Criteria Decision Making (MCDM) techniques are attractive in problems having multiple and conflicting objectives. This article develops a methodological framework providing insights to suitability of multi-criteria techniques in the context of operation energy alternatives namely Central Grid/Grid Extension, Solar Home Systems and Microgrids in India. The model was built using the Analytic Hierarchy Process (AHP) with empirical data from various sources. Several parameters like generation cost, price, losses, reliability, capacity, availability, and constraints (geological/local) were investigated. Based on the scheme developed by Saaty—the AHP and Fuzzy Sets using MATLAB these multi-criteria are evaluated and compared. The analysis were carried out under two scenarios namely—environment and cost. Finally alternatives for energy generation were ranked based on the AHP and Fuzzy logic. The results indicate that MICROGRID is the ideal choice among the alternatives for energy generation in a decentralised way and is a possible solution for eliminating energy poverty.

Keywords: Renewable energy, sustainability, multi-criteria, decentralized, fuzzy sets, electrification

INTRODUCTION

Climate change is today recognized as one of the biggest threats to humanity and nature. Our dependence on fossil-based fuels is the most significant contributor to climate change; thus addressing the energy issue is fundamental to tackling climate change. Renewable energy (RE) provides a potential way forward in reducing emissions while meeting future energy needs of both developed and developing countries [1.] Renewable energy is one of the cleanest sources of energy options with almost no pollution or carbon emissions and has the potential to significantly reduce reliance on coal and other fossil fuels [2]. Over 1.25 billion people in the world have no access to electricity and of these, nearly 300 million live in India without grid connectivity. They resort to burning kerosene to produce light at night and use biomass for cooking.

Over 90 percent of dark households are concentrated in rural India [3]. Although official estimates indicate that 95% of Indian villages are electrified, fewer than 50% of Indian households actually consume electricity [4]. There is no dearth of programmes and agencies involved in electrifying remote places in India. Various government policies promote development of mini-grids, including RE-based mini-grids. Mini-grids are defined as one or more local generation units supplying electricity to domestic, commercial, or institutional consumers over a local distribution grid [3]. Given the problem of energy access in India, renewable energy sources provide a unique opportunity to shift to cleaner sources at the decentralized or distributed level [5]. In order to avoid the long term energy infrastructure lock-in, action is needed now for a transition from fossil fuel based power to renewable energy.

PART 1: ENERGY SCENARIO— CHALLENGES AND SUPPLY OPTIONS

The power sector in India is highly diverse with varied commercial sources for power generation like coal, natural gas, hydro, oil and nuclear as well as unconventional sources of energy like solar, wind, bio-gas and agriculture. The demand for power has been growing at a rapid rate and overtaken the supply, leading to power shortages in spite of manifold growth in power generation over the years. Industrialization, urbanization, population growth, economic growth, improvement in per capita consumption of electricity, depletion of coal reserve, increasing import of coal, crude oil and other energy sources and the rising concern over climate change have put India in a critical position. One of the primary challenges for India would be to alter its existing energy mix which is dominated by coal to greater share of cleaner and sustainable sources of energy. Renewable energy including large hydro constitutes for only 28.8% of overall installed capacity in India. The total renewable energy potential from various sources in India is 2,49,188 MW [Figure 1]. India till 31st March 2014 has been able to achieve only 12.95% of its renewable energy potential. The untapped market potential for overall renewable energy in India is 216918.39 MW which shows huge growth potential for renewable energy in India [4].

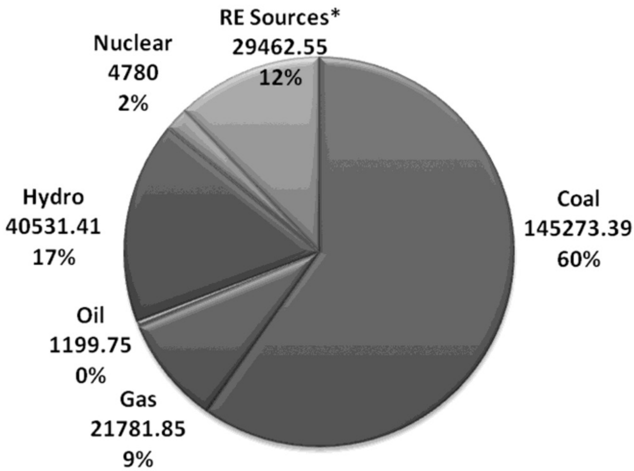


Figure 1. India—Source-wise installed electrical power capacity in MW [4]

Over the past 60 years India has taken rapid strides in the development of the power sector. In order to meet the increasing requirement of electricity, massive addition to the installed generating capacity in the country is required. While planning the capacity addition programme, the overall objective of sustainable development has been kept in mind. To meet the rate of consumption of electricity, 88.5 GW of electricity production capacity has been planned under the 12th Five Year Plan, and an estimated 100 GW will be scheduled in the 13th Plan.

To meet the energy requirement, increase in renewable energy sources have been planned. The Wind Energy sector is scheduled to grow at 10-15% to meet the demand for power [6]. Solar Energy is also estimated to reach 20 GW of energy capacity till 2022 due to heavy incentives offered by the government. The private sector is expected to play a major part, as by 2017-18, the private sector is expected to account for more than 35% of the country's power generation [7].

Growth of Renewable Energy in India

India has been making continuous progress in conventional as well as renewable power generation. The trajectory of growth of installed capacity since 2002 (start of the 10th five year Plan), 2007 (start of 11th Plan), and as of 30 November 2010 and 31st March 2014 is given in Table 1. It is observed from the table that renewable grid capacity has increased more than 5 times in a span of 8 years and this compares favorably with the EU and far exceeds that of the US. The growth so far is largely based on thermal energy but all other sources have also made important contributions [5].

Table 1. Trajectory of growth of installed power capacity in India.

Time period	Thermal		Hydro (>25MW)		Nuclear		Renewable Power	
	%	MW	%	MW	%	MW	%	MW
1.4.2002	70.85%	74429	25%	26269	2.59%	2720	**1.55%**	**1628**
1.4.2007	64.06%	87015	25.51%	34654	2.87%	3900	**7.55%**	**10258**
31.9.2010	63.95%	106518	22.41%	37328	2.7%	4560	**10.90%**	**18,155**
31.03.2014	69.23% *	168253	16.68%	40531	1.97%	4780	**12.12%**	**29462**

**** Includes coal, gas and oil.** (Source: MNRE), [5], [8], [9]

Impact of Policy and Vision 2022:
Off-grid Renewable Power Programs

During the last many years the share of renewable energy has steadily increased due to the initiative taken by Government of India. It is estimated that total share of renewable energy will be 15.9% by 2022. Indian renewable energy priorities are different from those of developed countries. Firstly, and most importantly, it provides energy access to large rural populations including those in inaccessible areas and meets the unattained demand in many other areas. Perhaps the remotest areas can get electricity only through renewable sources. Secondly there is another important, unrecognized consequence attributed to of off-grid applications. In one way or the other, they replace fossil fuels and can make a significant contribution to reduction in their consumption which is so important from the point of view of energy security. For instance, rural lighting replaces kerosene, a biogas plant or solar cooking system replace cooking gas, solar PV replaces diesel or furnace oil in various areas. It has a great strength in its ability to supply power in a decentralized and distributed mode which has the advantage of consumption at the production point and so reduces land and environmental concerns [10].

Features of Rural Electrification In India

In India the electricity sector has always confine to centralized electricity planning with large component of thermal power generation from fossil fuels and mainly dominated by coal. However, this centralized planning has not been able to keep the balance between demand and supply. This centralized electricity generation has resulted in inequities, external debate, and environmental degradation [11]. This situation mainly arrived from the adoption of centralized energy planning; it snubbed electricity demand of rural poor community [12].

At the time of Independence (1947), only about 1500 villages of the country had access to electricity. The scenario has changed significantly since then. It has been possible to extend electricity to about 538,296 numbers of villages out of a total of 593,732 as per census of 2001 villages thereby electrifying 90.8% of villages. As per rough estimates, out of this about 18,000 villages are located in remote and difficult areas and it is not possible to extend power supply to these villages through the existing power grid. Electrification of these villages, therefore, is proposed to be done through various sources of **distributed generation** including non-conventional sources of energy [6]. The electrification rate among actual rural households is much lower [13]. This is because the prevailing definition of electrification (since 2004) is that "A village will be deemed to be electrified if: basic infrastructure such as distribution transformer and distribution lines is provided in the inhabited locality as well as the hamlet where it exists and the number of households electrified should be at least 10% of the total number of households in the village" [14][15].

Rural electrification is an important component of Integrated Rural Development. Rural electricity distribution is costly due to dispersed distribution of loads in spread over areas. Majority of rural people have less per capita income and farmers cannot afford for energy derived from renewable energy sources, requiring higher capital investment during summer, their dependency increases on electrical supply [16]. Several studies suggest that rural electrification drives improvements in employment, health, agricultural productivity, and education [17], [18], [19]. For these reasons, policy makers have begun to view energy poverty with an increasing sense of urgency. While academics and policymakers agree that modern energy is a key input to development, there are fundamental disagreements concerning how best to expand energy access in rural areas. A number of organizations promote off-grid solutions such as solar lanterns, solar home systems, and microgrids over the alternative of existing grid infrastructure [20].

In view of all these points, Electrical power sector was recognized as a social sector in 1980s. From the time of independence, Government of India and State Electricity Boards have given priority for rural electrification and the phenomenal growth is evident from Figure 2.

PART 2—TECHNOLOGICAL ALTERNATIVES FOR REMOTE ENERGY GENERATION

In rural areas of India, two types of electrification are in progress. One is the electrification through connecting to conventional grid. The other is the electrification with renewable energies such as solar, biomass, hydro and so on. Many studies prove positive socio-economic impacts of the electrification with renewable energies in rural areas of developing countries including India [23]. Until recently, the main policy has been to extend the grid to villages in rural areas in order to emphasize productive uses for agriculture. Today, there is a new emphasis on making sure rural households have access to and adopt electricity [24, GREEN]. The method of 'connecting a village to be electrified to the nearest village that has been electrified' has led to an inefficient, unmanageable distribution network [25]. Rural people basically have three options or scenarios for the provision of electricity:

- Utility network grid-connection (via grid extension)
- Distributed-grid systems (often known as mini-grid systems or micro grids)

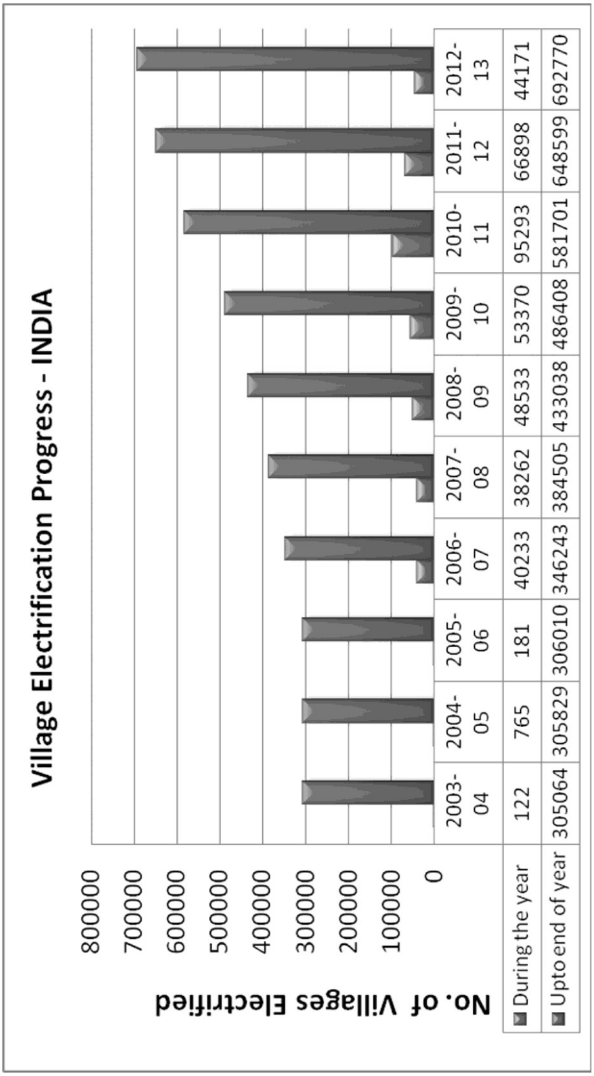


Figure 2. Growth and progress of village electrification—India [21], [22]

- Stand-alone system

Rural electrification cost comprises of high capital cost and high operating cost components. The effect of transmission and distribution losses may further increase the delivered cost. Therefore, **distributed electricity production**, defined as electricity-based production within the village that is not linked to a grid or to transmission or distribution networks provides a plausible medium-term solution to the electricity accessibility issue [26]. The government of India has identified the goal of electrifying every village in India, giving priority to distributed generating plants for villages too remote for extension of the conventional grid [27].

Benefits of Distributed Generation

The advantages of distributed generation or decentralised generation systems are numerous, including avoiding reliance on state utilities, which are not able to provide reliable supply or access. Other advantages include decreased reliance on fossil fuel-based electricity generation, decreased loss in transmission, which is currently estimated to be 40% in India, and direct employment opportunities within the villages, the sites of equipment and operation [26]. The US Energy Information Administration defines renewable energy as "energy that is naturally replenishing but flow-limited. Renewable energy is virtually inexhaustible in duration but limited in the amount of energy that is available per unit of time." Thus available options for rural electrification are—solar, wind, diesel and biomass [16].

Selecting the Appropriate Rural Electrification Strategy

In general, the appropriate rural electrification strategy will be largely based on whether or not the central grid is expected to reach a particular rural village. As the lifetime of most microgrids is about 15–25 years and the lifetime of solar home systems (SHS) is about 20 years. For example, a LED bulb must be replaced every 2 years, a battery every 4-5 years, solar panels every 10-12 years. This means systems tend to work for less than the perceived life. Whether or not the capital cost investment for microgrids or SHS is financially worthwhile depends on when the grid will reach the village [28]. The amount of time needed to recover the capital costs of setting up a microgrid system to be anywhere from 15 to 25 years [28]. A number of other factors also complicate this decision. Given the diversity of rural villages and households in India, selecting the appropriate rural electrification technology depends on the specific characteristics of the village in consideration. Location is the most important factor in determining if a village is electrified by the grid or not, showing that distance is one of the major barriers [29]. The characteristics of the three technological alternatives for remote electricity generation are given in Table 2. These data are used to evaluate and rank the technology alternatives under different criteria and two scenarios using AHP and Fuzzy logic.

PART 3: MULTI-CRITERIA DECISION ANALYSIS (MCDA)

The intense attention directed towards sustainable energy system gives high priority to renewable energy that would have a minimal impact on the environment, human health, and the quality of life [39]. The political, social, economic, and environmental importance of energy planning, to meet the ever-increasing energy demand with an adequate energy supply, renders the evaluation of different energy projects a major challenge for policy makers. This applies in particular for renewable energy sources (RES) because their particular features (decentralized production, localized and short-term cost, distributed and long-term benefits, involvement of many stakeholders, and multiple-evaluation criteria) entail the use of specific instruments to choose the optimum option. The use of multi-criteria decision analysis techniques provides a reliable methodology to rank alternative RES projects in the presence of numerous objectives and constraints [40]. Multi-Criteria Decision Making (MCDM) techniques are gaining popularity in sustainable energy management. The techniques provide solutions to the problems involving conflicting and multiple objectives [41]. Several methods based on weighted averages, priority setting, outranking, fuzzy principles and their combinations are employed for energy planning decisions [42].

Overview of Multi-Criteria Decision-Making Methods

Multi-criteria decision making (MCDM) methods have been applied to several different types of energy problems over the past three decades. The advantage of these models is that they allow for the evaluation of multiple, sometimes conflicting, criteria. Unlike simple cost-benefit models that are uni-dimensional, multi-criteria models

Table 2. Technology Characteristics of Grid Extension, Solar Home Systems, and Microgrids for Remote Rural Villages. [30]

Characteristic	Grid Extension	Solar Home Systems	Micro-grids
Reliability/ Power Quality	Low reliability, especially for rural areas that are not considered profitable because of low demand	Reliable power quality as long as the load is within the system's initial capacity. Low-quality end use appliances, replacement parts, and lack of standards may negatively affect reliability of system overall [31]	End-use appliances and replacement parts overall more reliable than those for SHS. Varies, though coupling generation sources and including energy storage device can improve power quality
Cost of Generation for Producers	For remote rural villages, can range from Rs. 3.18/kWh to Rs. 231/kWh, high range is mostly due to varying distances from central grid [32]	About Rs. 37/kWh84 [31]	Around Rs.23 to 33/kWh (varies by generation source, e.g., micro-hydro, biomass, solar PV, wind-solar)[33]
Price of Electricity for Consumers	Usually estimated to be Rs. 3/kWh, though this varies greatly by customer category; monthly costs increase with extent of usage	High per kWh costs; total upfront cost about Rs. 45,000 for a small home system[34]	High per kWh cost, but typical weekly/monthly rates are of the order of Rs. 100 to 200/month **[35]**
Load/Capacity	Unlimited capacity, although there is often load shedding during times of peak demand**[36][37]**	Limited capacity; small loads only (e.g., lighting, cell phone charging).	Limited capacity but greater than that of SHS; currently most microgrids are limited to small loads
Losses	About 23.97% in 201288 **[38]**	Losses exhibited are based on inefficiencies of the components within the SHS (e.g. battery and inverter)	Overall fewer losses than with SHS; losses exhibited are still based on inefficiencies of the components within the microgrid; losses can also take place in distribution infrastructure of electricity
Generation Sources	Varies, e.g. nuclear, renewable sources, coal, gas, oil, hydro, etc.	Solar	Determined by local DG resources (e.g. micro-hydro, biomass, solar, wind)
Geographic- or Location-Based Constraints	Cost for supplier increases for more remote villages, difficult to extend power lines across hilly or forested areas	Most appropriate in areas with high levels of solar irradiation	Generation sources may depend on location, but microgrid location itself is flexible
Operation & Maintenance	Low O&M capacity, often takes days for the State distribution companies to fix a problem	Easy installation and relatively low amount of maintenance needed with proper battery use	Varies from low (solar PV) to high (biomass)

allow stakeholders to compare options across several dimensions. Criteria may include factors of financial performance in addition to technical, social, or even esthetic dimensions. Evaluations may be based on historical data or preference rankings by domain experts. These methods can handle both quantitative as well as qualitative criteria and analyze conflict in criteria and decision makers [42].

Most commonly used multi-criteria decision-making methods are:

- Analytic Hierarchy Process (AHP): This method was first introduced by Saaty [43]. The goal is at the top level, criteria are in middle levels, and the alternatives are at the bottom layer of the hierarchy.
- Analytic Network Process (ANP) [44] [45]. ANP, however, deals with the problem as a network of complex relationships between alternatives and criteria where all the elements can be connected [46].
- Preference ranking organization method for enrichment evaluation (PROMETHEE): This method is characterized by ease of use and decreased complexity [47].
- The elimination and choice translating reality (ELECTRE): This method is capable of handling discrete criteria of both quantitative and qualitative in nature and provides complete ordering of the alternatives [48].
- The technique for order preference by similarity to ideal solutions (TOPSIS): The basic concept of this method is that the selected alternative is the one that has the best value for all criteria, i.e. has the shortest distance from the negative ideal solution [49].
- Multi-attribute utility theory (MAUT): The theory takes into consideration the decision maker's preferences in the form of the utility function which is defined over a set of attributes, where the utility of each attribute or criterion doesn't have to be linear [50].

There are many discussions in the literature about which MCDM methodology is best to use, and which is the "right" method applied to a real life problem. Multi-criteria analysis is used to select the "best fitted" solution [51].

Multi-criteria Decision Analysis in Renewable Energy

Adopting and choosing alternative energy sources is a multidimensional decision making process that involves a number of different characteristics at different levels: economic, technical, social, and environmental [52] [53]. While renewable fuels offer many benefits such as being "free' and plentiful, power plants based on these fuels suffer from production and capacity limitations due to the variability of solar radiation and thermal currents throughout the day and year. These and other financial, technical and socio-economic trade-offs pose immense problems for policy makers and investors as they struggle to assess which renewable technological options are "best" in both the short-term and the long term, prompting some to ask:

- What criteria should be used to evaluate energy alternatives?
- Is a micro grid justifiable compared to extending existing grid network?
- What is the best among technology alternatives (Grid extension, SHS, Microgrid)?
- Which energy technology is better under different scenario (cost and environment)?
- Will the choice remain the same or differ with scenario?

The purpose of the study was to develop a method to help answer these questions. Toward that end, a comprehensive multicriteria decision making (MCDM) model was implemented to evaluate three different types of energy producing alternatives according to 8 key metrics. It is believed that this method and these results are of value to policy experts, investors and utility company executives responsible for making policy and investment decisions [54].

Analytic Hierarchy Process [AHP]

AHP is a multi-criteria decision making tool which provides to structure complex problems in a hierarchic manner, as a result it simplifies evaluating all of the criteria which are relevant with the decision that must be given [43]. All of the alternatives are compared pairwise based on each criterion by using a preference scale and a priority list of alternatives is achieved for each criterion [55].

Table 3. Preferences made on 1-9 scale

AHP scale of importance for comparison pair (a_{ij})	Numeric Rating	Reciprocal (decimal)
Extreme Importance	9	1/9 (0.111)
Very strong to extremely	8	1/8 (0.125)
Very strong importance	7	1/7 (0.143)
Strongly to very strong	6	1/6 (0.166)
Strong importance	5	1/5 (0.200)
Moderately to strong	4	¼ (0.250)
Moderate Importance	3	1/3 (0.333)
Equally to moderately	2	½ (0.500)
Equal importance	1	1 (1.000)

In AHP, decision makers quantify the importance of criteria by using Cheng's 1-9 scale which lies between "equal importance" to "extreme importance (Table 3). The complexity of problems can be organized systematically using AHP, which present the problems in format of a hierarchy relationship. Based on the hierarchy relationship, paired comparison was designed to calculate the relative weights of each criterion. The advantage of AHP, a qualitative and quantitative approach, was to find priority weights through paired comparison of attributes. The weights of the performance criteria, therefore, should be considered and further provide priorities for decision-makers to more precisely measure project performance and allot limited resources.[Pohekar]. The process of AHP is described as follows [43]:

Step 1: Describe of the evaluation issues
Step 2: Identify all criteria which affect the issues
Step 3: Construct the hierarchy structure
Step 4: Establish the paired matrices for comparison
Step 5: Calculate eigenvectors
Step 6: Consistency test.(acceptable if < 0.1) [Saaty].
Step 7: Normalization

After the Comparison matrix is formed, AHP terminates by computing an eigenvector (also called a priority vector) that represents the relative ranking of importance (or preference) attached to the criteria or objects being compared. The largest eigenvalue provides a measure of consistency [56].

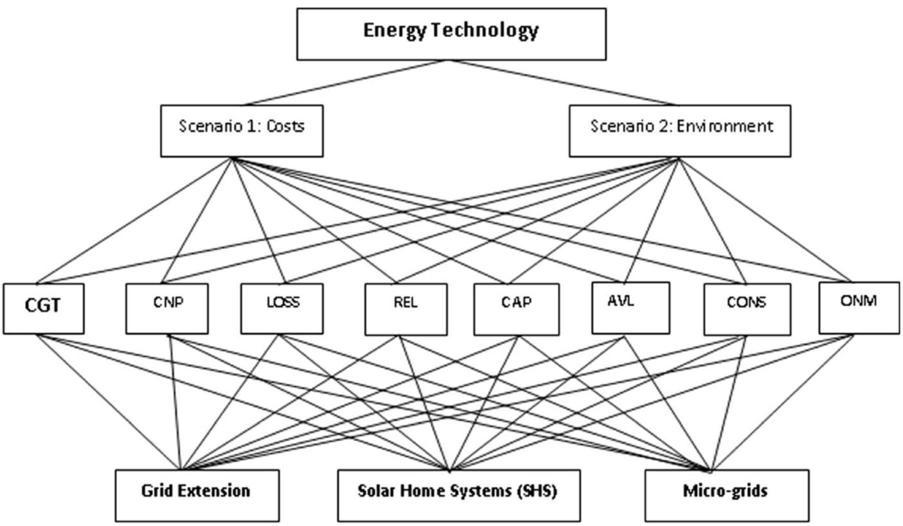
Setting up the Method to Rank Energy Technology Alternatives

The first step in AHP is to set up the hierarchy of criteria and alternatives. The structure for the selection/evaluation of the energy alternatives is illustrated in Figure 3. Historical data on the financial and environmental characteristics associated with each of the energy technologies were used. Data sources were selected for trustworthiness and overall validity; i.e., government sponsored studies or appearing in peer-reviewed journals.

From the above mentioned indicators, criteria and renewable energy sources, the model for sustainable energy planning in this work is established.

AHP Analysis

The rated data and the weights used in AHP simulations are shown in Table 4. Analyses were made following the completion of pairwise comparisons. The first of analyses is to check the consistency of judgments. In the AHP method, the consistency of matrixes in a pairwise comparison should be ensured. If the matrix is inconsistent,



CGT: Generation Cost **CNP: Price for Consumers** **LOSS: Losses**
REL: Reliability **CAP: Capacity/Load** **AVL: Availability**
CONS: Constraints **ONM: Operation and Maintenance**

Figure 3. The hierarchical structure for the selection/evaluation of the energy alternatives

Table 4. Data used in AHP analysis

S. NO.	Criteria	GRID	SHS	MICROGRID
	Quantitative	Rated data		
1	COST (GENERATION/kWh) Rs	3.33 to 231	37	33
2	PRICE (CONSUMERS) Rs	3 /kWh or 300/month	45000/home	100-200/month
3	LOSSES	24%	20%	15%
	Qualitative	Weights – "the higher the better"		
4	RELAIBILITY	0.5	0.6	0.9
5	CAPACITY/LOAD	0.9	0.4	0.8
6	SOURCES (AVAILABILITY)	0.7	0.8	0.8
7	CONSTRAINTS (GEO/LOCAL)	0.6	0.7	0.9
8	O&M	0.5	0.9	0.7

evaluations must be made until a consistency is achieved. The consistency ratio (CR) must be smaller than 0.10. The second stage of analysis is to calculate relative weights of both main criteria and sub-criteria.

After identifying the criteria and the alternatives, they must be placed into an AHP hierarchy, which is then used to construct the pairwise comparison matrix (PCM). For this, it is necessary to estimate the weights of the decision's criteria. This is done via measurement of AHP, which is based in the theory defined by Saaty [43]. Therefore, as shown in a set of tables (Tables 5 to 8), it is assumed one weight to each pairwise comparison. In this way it is considered for all criteria and

Table 5. PCM: Alternative x Alternative (Criteria 1 and Criteria 2)

Criteria 1: Generation Cost (GCT)						Criteria 2: Consumers Price (CNP)				
	GRID	SHS	MGRID	RW			GRID	SHS	MGRID	RW
GRID	1.00	0.33	0.20	0.1048		GRID	1.00	5.00	3.00	0.6370
SHS	3.00	1.00	0.33	0.2578		SHS	0.20	1.00	0.33	0.1047
MGRID	5.00	3.00	1.00	0.6374		MGRID	0.33	3.00	1.00	0.2582
CR = 0.0449						CR = 0.04745				

Table 6. PCM: Alternative x Alternative (Criteria 3 and Criteria 4)

Criteria 3: Losses (LOSS)						Criteria 4: Reliability (REL)				
	GRID	SHS	MGRID	RW			GRID	SHS	MGRID	RW
GRID	1.00	9.00	5.00	0.7523		GRID	1.00	0.33	0.11	0.0693
SHS	0.11	1.00	0.33	0.0695		SHS	3.00	1.00	0.20	0.1773
MGRID	0.20	3.00	1.00	0.1781		MGRID	9.00	5.00	1.00	0.7534
CR 0.03462						CR = 0.04468				

Table 7. PCM: Alternative x Alternative (Criteria 5 and Criteria 6)

Criteria 5: Capacity / Load (CAP)						Criteria 6: Availability (AVL)				
	GRID	SHS	MGRID	RW			GRID	SHS	MGRID	RW
GRID	1.00	9.00	3.00	**0.6740**		GRID	1.00	0.20	0.14	**0.0719**
SHS	0.11	1.00	0.20	**0.0617**		SHS	5.00	1.00	0.33	**0.2789**
MGRID	0.33	5.00	1.00	**0.2643**		MGRID	7.00	3.00	1.00	**0.6492**
CR = 0.0331						CR = 0.08299				

Table 8. PCM: Alternative x Alternative (Criteria 7 and Criteria 8)

Criteria 7: Constraints Geog/Local (CONS)						Criteria 8: Operation & Maintenance (ONM)				
	GRID	SHS	MGRID	RW			GRID	SHS	MGRID	RW
GRID	1.00	3.00	5.00	**0.6401**		GRID	1.00	3.00	5.00	**0.6376**
SHS	0.33	1.00	3.00	**0.2568**		SHS	0.33	1.00	3.00	**0.2578**
MGRID	0.20	0.33	1.00	**0.1031**		MGRID	0.20	0.33	1.00	**0.1046**
CR = 0.04493						CR = 0.0431				

each final possible alternative (renewable energy sources), according to the data presented in Table 4.

Pairwise Comparison Matrix: PCM

To find the classification of the energy sources, their relative weights (RW), according to each parameter presented in Table 5 to Table 8, are therefore multiplied by the relevant RW estimated in Tables 9 and 10. It is assumed one weight to the pairwise comparisons, taking into account only the criteria, and with regards the classification of priority.

Table 9. Pairwise Comparison Matrix: Scenario 1—Environment

PCM: (Criterion* Criterion) Scenario 1: Environment									
	GCT	CNP	LOSS	REL	CAP	AVL	CONS	ONM	RW
GCT	1.00	0.33	1.00	1.00	9.00	0.33	3.00	3.03	**0.134**
CNP	3.00	1.00	3.00	1.00	9.01	0.33	3.00	1.00	**0.166**
LOSS	1.00	0.33	1.00	0.20	5.00	0.20	1.00	0.33	**0.059**
REL	1.00	1.00	5.00	1.00	9.00	1.00	3.03	3.00	**0.194**
CAP	0.11	0.11	0.20	0.11	1.00	0.11	0.11	0.14	**0.015**
AVL	3.00	3.00	5.00	1.00	9.00	1.00	3.00	3.00	**0.262**
CONS	0.33	0.33	1.00	0.33	9.00	0.33	1.00	0.33	**0.062**
ONM	0.33	1.00	3.00	0.33	7.00	0.33	3.00	1.00	**0.107**
CR = 0.0869									

Table 10. Pairwise Comparison Matrix: Scenario 2—Costs

PCM: (Criterion* Criterion) Scenario 2: Costs									
	GCT	**CNP**	**LOSS**	**REL**	**CAP**	**AVL**	**CONS**	**ONM**	**RW**
GCT	1.00	0.33	5.00	0.33	7.00	0.33	5.00	3.03	**0.132**
CNP	3.00	1.00	5.00	1.00	9.00	0.33	3.00	1.00	**0.163**
LOSS	0.20	0.20	1.00	0.11	3.03	0.11	0.33	0.33	**0.028**
REL	3.00	1.00	9.00	1.00	5.00	0.33	3.00	3.03	**0.184**
CAP	0.14	0.11	0.33	0.20	1.00	0.11	0.20	0.20	**0.019**
AVL	3.00	3.00	9.00	3.00	9.00	1.00	7.00	5.00	**0.342**
CONS	0.20	0.33	3.00	0.33	5.00	0.14	1.00	1.00	**0.058**
ONM	0.33	1.00	3.00	0.33	5.00	0.20	1.00	1.00	**0.074**
CR = 0.09218									

AHP Final Classification of Weights

The screened scenarios are connected with environment and costs, respectively. The results of this multiplication, the sum of these results (FRW—Final Relative Weights) and the energy source classification are shown in Tables 11 and 12.

FUZZY ANALYSIS

In many decision-making situations, it is relatively difficult to obtain exact numerical values for the criteria or attributes [57] [58]. Thus, many parameters cannot be evaluated accurately and the data of different subjective criteria and their weights are usually expressed in linguistic terms by the decision maker [59]. In order to overcome this uncertainty in human judgment, fuzzy logic can be applied which deals with vague information by applying membership functions.

The fuzzy logic of the underlying model was implemented by using the software MATLAB, under multi-rules-based decision and multi-sets considerations. The Mamdani method was applied in the fuzzy inference process and the method of the center of gravity in the defuzzyfication process. The number of linguistic terms in each fuzzy set determines the number of rules. In most applications certain states can be neglected either because they are impossible or because a control action would not be helpful. It is therefore sufficient to write rules that cover only parts of the state space. The definition of linguistic variables and rules are the main design steps when implementing a Mamdani controller. Besides, an appropriate priority classification of the criteria is essential to corroborate the outcome of the fuzzy meth-

Table 11. AHP Final Classification—Environment Scenario

AHP Final Classification - 1. Environment Scenario										
	GCT	CNP	LOSS	REL	CAP	AVL	CONS	ONM	FRW	CL
GRID	0.014	0.106	0.044	0.013	0.010	0.019	0.040	0.068	0.315	2
SHS	0.035	0.017	0.004	0.034	0.001	0.073	0.016	0.028	0.208	3
MGRID	0.086	0.043	0.010	0.146	0.004	0.170	0.006	0.011	0.477	1

Table 12. AHP Final Classification—Costs Scenario

AHP Final Classification - 2. Costs Scenario										
	GCT	CNP	LOSS	REL	CAP	AVL	CONS	ONM	FRW	CL
GRID	0.014	0.104	0.021	0.013	0.013	0.025	0.037	0.047	0.273	2
SHS	0.034	0.017	0.002	0.033	0.001	0.095	0.015	0.019	0.216	3
MGRID	0.084	0.042	0.005	0.139	0.005	0.222	0.006	0.008	0.511	1

odology. Qualitative criteria are expressed through weights (defined in the interval from 0 to 1.0) to be applied in the fuzzy sets. The fuzzy sets that characterize each criterion are shown in Figure 4 (capacity under cost criteria and availability under environment criteria are depicted as sample graphs). The number of membership functions used in each criterion of the fuzzy set and the multi-rules are determined according the criteria relevance for the two different scenarios.

Fuzzy set theory is integrated to overcome the ambiguity in the preferences. In the literature, different studies had used fuzzy analysis in energy planning and energy policy. [60] The final classification of the renewable energy sources is presented in Table 13 and 14. These are calculated by using the Fuzzy logic and is associated with environment

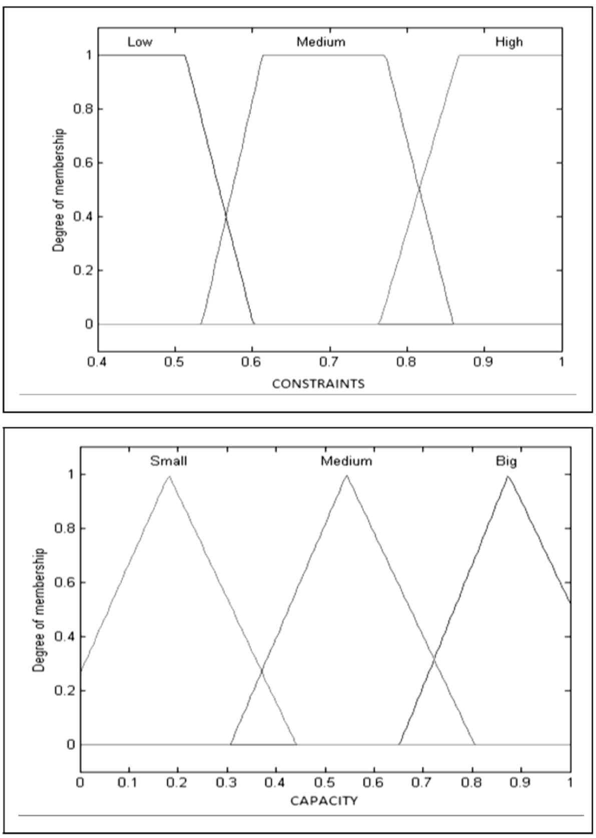


Figure 4. Fuzzy results—Capacity (Cost criteria) Availability (Environment criteria)

and costs scenario.

Table 15 presents the final relative weights and the classification according to the results achieved by AHP and fuzzy logic, regarding environment and costs scenarios. The results of Fuzzy and AHP analysis for the alternatives closely resemble each other and the same is discussed below.

RESULTS AND DISCUSSIONS

As seen from the above table, "Microgrids" seems to be the best technology for sustainable energy planning according to the AHP methodology and Fuzzy Analysis. The above results indicate that, the renewable source classification is exactly the same if compared with the AHP method or fuzzy logic outcome. These results corroborate the use of both methodologies for the analysis of the main characteristics of renewable energy sources. Accordingly, the Micro-Grid is the most appropriate choice for both environment and costs scenarios. It is central to emphasize that this study may consider several criteria and scenarios. This can be done simply evaluating and changing the AHP and the fuzzy methodology (sets and rules) in each case of the analysis. The following observations can be made from the study.

- The results closely agree for both Fuzzy and AHP analysis with ranking of the technology options.
- The Microgrid option scores over remaining two alternatives both under cost and environment scenario for both AHP and Fuzzy analysis. Also the margin of score is relatively high.
- Under Fuzzy Analysis with Environment Scenario—the ranking order is 3-2-1 instead of 2-3-1 as observed in other 3 cases. But the difference between scores or relative weight between GRID extension and SHS is very marginal and hence the results are fairly consistent. In addition the relative weight for Micro grid is relatively far away ahead the other two.
- The Microgrid option has an edge over SHS and grid extension both under cost and environment scenario considering both AHP and Fuzzy analysis. Also the relative weight is far ahead of the remaining alternatives. The difference between the FRW as well

Table 13. Fuzzy results—Scenario: Environment

SCENARIO - ENVIRONMENT										
	GCT	CNP	LOSS	REL	CAP	AVL	CONS	ONM	MEAN	RANK
GRID	0.6813	0.3088	0.3675	0.1656	0.6106	0.4363	0.5029	0.1239	0.3996	3.00
SHS	0.2279	0.3956	0.3698	0.3457	0.1599	0.5532	0.5091	0.6813	0.4063	2.00
M-GRID	0.3319	0.4003	0.5175	0.6684	0.4715	0.5532	0.8235	0.4923	0.5323	1.00

Table 14. Fuzzy results—Scenario: Costs

SCENARIO - COSTS										
	GCT	CNP	LOSS	REL	CAP	AVL	CONS	ONM	MEAN	RANK
GRID	0.8481	0.3896	0.5464	0.1176	0.8623	0.5373	0.3908	0.1625	0.4818	2.00
SHS	0.2997	0.5046	0.5486	0.3705	0.1920	0.6925	0.3956	0.8142	0.4772	3.00
M-GRID	0.4301	0.5105	0.6687	0.8207	0.6427	0.6925	0.6877	0.5906	0.6304	1.00

Table 15. Final classification in AHP and Fuzzy sets: Environment scenario and Costs scenario

Technology	Environment Scenario				Cost Scenario			
	AHP		FUZZY		AHP		FUZZY	
	FRW	RANK	MEAN	RANK	FRW	RANK	MEAN	RANK
GRID	0.3149	2.00	0.3996	3.00	0.2734	2.00	0.4818	2.00
SHS	0.2082	3.00	0.4053	2.00	0.2161	3.00	0.4772	3.00
MICROGRID	0.4769	1.00	0.5323	1.00	0.5105	1.00	0.6304	1.00

as Mean for SHS and grid is minimum for both AHP and Fuzzy analysis.

The use of multi-criteria decision analysis (MCDA) techniques provides a reliable methodology to rank alternative renewable energy resources, technologies and projects in the presence of different objectives and limitations. Different methods often produce different results even when applied to the same problem using same data. There is no better or worse method but only a technique that fits better in a certain situation. AHP is the most used methodology of all MCDM methods. This can be credited to its simple structure and the ability of an analyst to negotiate results until consistency is achieved, offering near consensus on judgment. This model/analysis can be used to rank electricity producing technologies based on different criteria.

As the central grid is still far from reaching all remote villages, a number of pilot projects have been successfully implemented in India using microgrids [30], namely:

1. Gram Oorja's installation of a solar powered microgrid in Darewadi, Pune in Maharashtra
2. Mera Gao Power serving a number of villages in the state of Uttar Pradesh
3. Sagar Islands in the Sunderbans region of West Bengal.

These microgrids are not just a theoretical solution, but have actually translated to successful small-scale projects. [30]. Thus, microgrids have been shown to be successful at the project level in different contexts. Microgrid developers face the continuing challenges of obtaining the initial investment needed to get the project off the ground as well as figuring out how to create a system that can provide sufficient electricity to meet effective demand. However, in the context of meeting rural India's electricity needs, the challenge now is to replicate these individual project level successes at a wider scale (i.e., to scale up microgrids). In order to do so, it is essential to ensure that microgrid projects meet the criteria of feasibility so that developers are willing to undertake such projects in the first place, and also of sustainability so that such projects can be operational for many years.

SUMMARY AND CONCLUSIONS

Energy is vital for development and if India is to move to a higher growth trajectory than is now feasible, it must ensure the reliable availability of energy. Energy is central to achieving the interrelated economic, social, and environmental aims of sustainable human development. But if India is to realize this important goal, the kinds of energy India produces and the ways it uses them will have to change.

The AHP model ranked three primary technology alternatives: conventional Grid, smart Microgrid and Solar Home Systems (SHS), in terms of overall benefits. The smart Microgrid tops the list. The results of the multi-criteria decision analyses suggest that the Microgrid is the best energy technology alternative. The ranking of the other alternatives in descending order is determined as Grid extension followed by solar home systems. Also, the evaluation of criteria indicates that environmental effects are more important in this problem of technology selection. To summarize, this analysis gives valuable information on the great potential of renewable sources of energy for the improvement of system management, taking into consideration economic and environment aspects. Future studies could be done to broaden the scope of this model to include other alternatives for an effective energy strategy for INDIA and other countries.

India needs to realize the vast potential of renewable energy and need to step up effort for attaining the goal of "20, 11, 20, 20" by 2020 i.e. 20% reduction in GHG, 11% reduction in consumption of energy by bringing about attitudinal changes, 20% share of renewable energy and 20% conservation of energy from the year 2011 till 2020. These targets are attainable and not only provide cleaner energy but also open a new field for providing employment opportunities to millions of people who are unemployed or disguised employment. This momentum then needs to be maintained so that India attains a target of having 70% renewable energy use by 2050.

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