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Application of multi-criteria decision analysis tool for design of a sustainable micro-grid for a remote village in the Himalayas

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Abstract: Decision analysis tool is utilised for the design and analysis of a microgrid with a perspective of sustainable development for a remote location in the hilly terrain of Himalayas. The microgrid design is based on the locally available energy resources, such as solar, wind, running water streams to meet the electrical load demand. The village selected has no access to electricity till date. A door-to-door survey is conducted to project the current and future load demand of the community. The complexity in designing sustainable energy system due to the inclusion of multiple criteria with multiple objectives and scenarios has increased to a great extent. Involvement of multiple stakeholders with differing views and various factors such as social, technical, environmental, economic and political/institutional, makes the process more tedious. For a successful design of the microgrid for such locations, a synergy needs to exist between differing viewpoints of stakeholder when multiple criteria with various scenarios are considered. Multiple criteria decision analysis tools are best suitable for such scenarios especially for energy planning based on renewable energy technologies. The process outlined in this paper will be helpful for successful design of sustainable microgrids for unelectrified and rural location in developing nations.

1 Introduction

In the twenty-first century due to technological developments, energy has become an integral part of our daily livelihood, yet many millions are suffering from energy poverty, i.e. with no access to basic energy services [1]. Due to energy poverty, currently 38% (2742 million) people globally rely on solid biomass for cooking out of which 793 million are in Africa, 819 million are in India, 453 million are in China and 65 million in Latin America, respectively, as per International Energy Agency [2]. Approximately around 3.5 million premature deaths are being reported due to household air pollution mostly resulting from the use of solid fuels such as wood, charcoal, etc. [3–5]. Even with technical breakthrough, global electricity access is far from reality affecting 16% (1186 million) of world's population mostly from Sub-Sharan Africa and India with the majority concentrated in rural and remote locations [6, 7]. Modern energy services have a significant effect and can quickly enhance the life of many people in many ways especially in developing nations. United Nation (UN), general assembly on 25th September 2015, has also passed a resolution, 'Transforming our world: the 2030 Agenda for Sustainable Development (SD)' comprising SD goal 7 with a pledge to 'ensure access to affordable, reliable and modern energy to all' [8]. However, this target set by UN is highly unlikely to be achieved, as more than 0.5 billion people in rural and remote locations of developing nations will not have any access to electricity along with 2.6 billion without access to proper cooking facilities in 2040 [1, 7]. Also, the energy demand is projected to rise at least in coming three decades led mostly by India and China with a contribution over 40% [9].

In developing countries such as Africa and India, economical and reliable energy services to a certain extent can reduce poverty and improve health conditions. India's current economic and development goals to make it a manufacturing base is still facing challenges and needs to further expansion of its energy sector has become mandatory [10]. India's generation capacity has increased recently but coal-based thermal plants are dominating a significant contribution around 61.45% of its electricity production, and only 30% comes from renewable energy sources [11, 12]. Recently, with the signing of the climate of Paris agreement (COP 21), it must take certain steps to keep low levels of greenhouse gas emission to maintain lower carbon footprint [13]. To continue its streak on the path of development and to meet its growing energy demand, it must tap its immense potential of renewable energy [10]. The use of renewables resources with a perspective of sustainability can help to achieve its development goals without violating COP 21 agreements. Due to which, India is aiming higher generation from renewable energy sources by increasing its capacity from 32 GW in 2014 to 175 GW by 2030 [11, 14]. Even with the inclusion of several new policies and government initiative to meet the energy need of its people, the road ahead seems full of challenges with increasing population growth which in term will increase its energy demand. India with a home of 1.3 billion people is still struggling to provide electricity access to 240 million of its population [6]. Till, December 2016, ∼6000 rural areas are still unelectrified [15]. For achieving its sustainable development goals with 100% electrification at disintegrated levels in a remote location, a proper synergy has to be found while planning energy system [7, 11]. Complexity levels of the power system design, particularly at the disintegrated level, has increased due to the presence of multiple stakeholders with differing views. Several energy system projects accompanying best technologies have been reported to fail in the literature due to the negligence of social and cultural characteristics of the targeted community [4, 7, 11, 16, 17]. Sustainable microgrid for remote location based on locally available energy resources are also characterised with many complexities with multiobjective problems [5, 16, 18, 19]. Multi-criteria decision analysis (MCDA) methods have been proved to efficiently provide a solution to such complex problems considering each and every aspects by keeping in the same framework simultaneously [11, 20]. Authors in [21] have utilised MCDA techniques namely analytical hierarchical process (AHP) to evaluate energy project based on three criteria (social, economic and environment) and 14 sub-criteria for Turkey. The use of MCDA with the integration of geographic information system to determine the suitable location for distributed generators based on wind turbines has been reported in [18]. Application of decision analysis tools in renewable energy planning, and implementation with different indicators has been presented in detail by [22–25]. Renewable energy system design based on locally available resources for electrification of remote locations in India is studied in [26–28]. Fuzzy AHP method is utilised to evaluate energy systems based on sustainable indicators for India [29]. The authors in [30] have outlined a framework to design rural electrification system for a case study based on a total of 18 performances indicators considering two scenarios. Most of the scholarly work described in the literature have failed to find all the paradigm of sustainability while evaluating remote electrification system [11] and have taken at most 18 key performance indicators (KPIs) recently reported in [30] considering very few scenarios.

In this work, a sustainable microgrid is evaluated based on a total of five main criteria (social, technical, environmental, economical and political/institutional) with 20 KPI or sub-criteria in 12 different scenarios. Solar photovoltaics (PV), a small hydrokinetic system based on the run of river schemes (HRoR) with small wind turbine (SWT) system and diesel generator (DG) is considered as energy sources along with battery and pump hydro schemes (PHS) as storage system nine alternatives to an isolated centralised microgrid system and three in the decentralised scheme have been considered for evaluation based on 20 KPIs in 12 scenarios. The paper organisation is as follows: Section 2 describes the characteristics of the targeted location along with specific details regarding the alternatives, KPIs and scenarios. Section 3 presents the MCDA-based evaluation followed by results and conclusion, in Sections 4 and 5, respectively.

2 Site characteristics and parameter selection for evaluation

Following the methodological framework as illustrated in [30], relevant data was collected to carry out the analysis. The details are as follows.

2.1 Target village characteristics

Tajo village is located in the beautiful mountain regions of North East India in Chaynagtajo Tehsil of East Kameng District. Currently, there are 20 households with a total population of 158 out of which 76 are male, and 82 are female. Approximately 80% of the population is below poverty line according to the census data [31]. The sub-district headquarters Chayangatjo and district headquarters Seppa are located 12 and 70 km, respectively, from the village. The average annual rainfall in the region is between 1997 and 2400 mm and temperature ∼8–21°C [32]. The annual average daily radiation in the region is around 3.91 kW/m^2/day with an annual average wind speed of 4.2 m/s [33]. Almost 7–8 months rain is present in the region with heavy rainfall during April to August months. Kameng river's tributary Para River is located near to this village, and it has an enormous potential to tap energy from it. Central electricity authority [34], India has identified a great potential for generating ∼4637 MW electricity through several hydro-electric projects in Kameng river basin. Twenty-eight hydroelectric schemes with a total capacity of 3940 MW have been allowed in the region [35] which is still under construction and might take many years to complete facing several challenges from

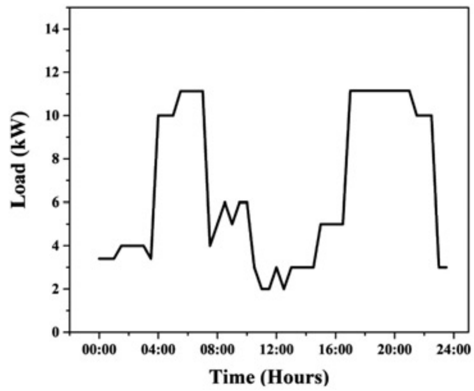

Fig. 1 *Power consumption profile on hourly basis*

natural issues (landslides, rain etc.) to social problems in the area. As per door-to-door survey conducted with the help of a community leader in the area during December 2016, no access to electricity was present in the village. However, the State Government Power Department has installed transmission lines and a distribution substation to electrify the village in future. This whole region due to heavy rainfall faces frequent mountain slides and landslides which in turn destroy the transmission lines and will certainly make the power supply from the grid with frequent outages. Even the road connectivity is very difficult in the region and to restore the power lines during such situations will be tedious and time taking.

However, an isolated sustainable microgrid based on the locally available renewable resources could be the key. For designing the microgrid, a daily electrical consumption profile was derived based on the survey conducted. Fig. 1 shows an approximate power consumption pattern on an hourly basis for a typical day of the village. The total connected load of the village is ∼17.63 kW, the peak load of 11.15 kW and an average base load of 5.5 kW.

2.2 Potential energy alternatives

The target community has tangible energy resources (solar, wind, river etc.) for power generation already outlined in Section 2.1. Upon discussion with the experts and other stakeholders from the community, a total of 12 alternatives (nine in a centralised system and three in decentralised system) based on the combination of PV, SWT, HRoR and DG as an energy source along with battery and PHS as storage is taken for further analysis. The specific details of the alternatives are illustrated in Table 1.

Table 1 Alternatives

Sl. no	Alternative	Configuration
1	PV + battery (A1)	centralised
2	HRoR + battery (A2)	centralised
3	PV + HRoR + battery (A3)	centralised
4	PV + DG + battery (A4)	centralised
5	HRoR + DG + battery (A5)	centralised
6	PV + HRoR + DG + battery (A6)	centralised
7	HRoR + PHS (A7)	centralised
8	PV + RoR + PHS (A8)	centralised
9	RoR + DG + PHS (A9)	centralised
10	PV + battery (A10)	decentralised
11	SWT + battery (A11)	decentralised
12	PV + SWT + battery (A12)	decentralised

Table 2 List of key performance indicators

Sl. no	Criteria		KPI/sub-criteria
1.	technical	I.	efficiency (EFF)
		II.	useful life (UL)
		III.	scalability (SI)
		IV.	availability of local energy resources (AVLR)
2.	social	V.	public acceptance (PA)
		VI.	human development index (HDI)
		VII.	human safety and convenience (HSC)
		VIII.	employment opportunities (EO)
3.	economical	IX.	capital cost (CC)
		X.	installation cost (IC)
		XI.	operation and maintenance cost (O & M)
		XII.	fuel cost (FC)
4.	environmental	XIII.	pollution (P)
		XIV.	water quality (WQ)
		XV.	aquatic life impact (ALI)
		XVI.	land use (LU)
5.	political/ institutional	XVII.	local ownership (LO)
		XVIII.	human capital (HC)
		XIX.	existing policy compatibility and support (EPCS)
		XX.	project stability (PS)

2.3 *Criteria/KPI selection*

Ilskog in [36, 37] has given 39 specific indicators based on five dimensions of sustainability (social, technical, economical, environmental and political/institutional) to evaluate alternatives for rural electrification. The authors in [11] have also specified a list of KPIs mostly used in the analysis of energy system. The selection of KPIs is dependent much on the available data and relevance to the project along with interest of stakeholders [30]. The detailed data collected from the village was presented to a group of experts from academia/industry working in rural electrification and concerning other stakeholders. A total of five criteria with 20 sub-criteria/KPI were chosen to evaluate the alternatives upon the suggestions of the experts. Table 2 shows the details about the KPIs.

2.4 *Scenarios details*

As outlined in Section 1, most of the energy system evaluations have been done considering only a few scenarios. Scenarios are

Table 3 List of scenarios

Sl. no	Scenarios
1	technical = social = economical = environmental = political (AE)
2	technical > social > economical > environmental > political (T1)
3	technical > environmental > social > political > economical (T2)
4	technical > political > social > economical > environmental (T3)
5	social > technical > economical > environmental > political (S1)
6	social > environmental > political > economical > technical (S2)
7	economical > social > technical > environmental > political (E1)
8	economical > environmental > social > political > technical (E2)
9	environmental > technical > social > economical > political (EV1)
10	environmental > social > technical > political > economical (EV2)
11	political > social > technical > environmental > economical (P1)
12	political > environmental > social > economical > technical (P2)

Table 4 Pairwise comparison matrix (criterion × criterion) considering scenario T1

	PA	HDI	HSC	EO	EFF	UL	SI	AVLR	CC	IC	O & M	FC	P	WQ	ALI	LU	LO	HC	W
PA	1.00	1.00	1.00	1.00	1.00	0.33	0.33	0.20	3.00	3.00	3.00	3.00	3.00	3.00	5.00	3.00	5.00	3.00	**2.00**
HDI	1.00	1.00	2.00	2.00	0.33	0.20	0.20	0.25	3.00	3.00	5.00	3.00	3.00	3.00	5.00	5.00	3.00	3.00	**3.00**
HSC	1.00	0.50	1.00	1.00	0.50	0.20	0.20	0.25	3.00	3.00	3.00	5.00	5.00	3.00	3.00	5.00	5.00	5.00	**3.00**
EO	1.00	0.50	0.50	1.00	0.33	0.25	0.20	0.20	3.00	3.00	3.00	3.00	5.00	5.00	5.00	3.00	5.00	3.00	**3.00**
EFF	1.00	3.00	3.00	3.00	1.00	1.00	1.00	1.00	5.00	5.00	5.00	5.00	5.00	5.00	5.00	5.00	5.00	5.00	**5.00**
UL	3.00	5.00	5.00	4.00	1.00	1.00	1.00	1.00	5.00	5.00	5.00	5.00	5.00	5.00	5.00	5.00	5.00	5.00	**3.00**
SI	3.00	5.00	5.00	5.00	1.00	1.00	1.00	1.00	5.00	5.00	5.00	5.00	5.00	5.00	5.00	5.00	5.00	5.00	**3.00**
AVLR	5.00	4.00	4.00	5.00	1.00	1.00	1.00	1.00	5.00	5.00	5.00	5.00	5.00	5.00	5.00	5.00	5.00	3.00	**5.00**
CC	0.33	0.33	0.33	0.33	0.20	0.20	0.20	0.20	1.00	1.00	2.00	1.00	3.00	3.00	3.00	3.00	5.00	2.00	**3.00**
IC	0.33	0.33	0.33	0.33	0.20	0.20	0.20	0.20	1.00	1.00	2.00	1.00	3.00	5.00	3.00	3.00	3.00	3.00	**3.00**
O & M	0.33	0.20	0.20	0.33	0.20	0.20	0.20	0.20	0.50	0.50	1.00	1.00	1.00	3.00	3.00	5.00	3.00	2.00	**3.00**
FC	0.33	0.33	0.33	0.33	0.20	0.20	0.20	0.20	1.00	1.00	1.00	1.00	3.00	1.00	3.00	2.00	3.00	3.00	**3.00**
P	0.33	0.33	0.33	0.20	0.20	0.20	0.20	0.20	0.33	0.33	1.00	0.33	1.00	1.00	2.00	1.00	3.00	3.00	**2.00**
WQ	0.33	0.33	0.33	0.20	0.20	0.20	0.20	0.20	0.33	0.20	0.33	1.00	1.00	1.00	1.00	1.00	3.00	2.00	**3.00**
ALI	0.20	0.20	0.20	0.20	0.20	0.20	0.20	0.20	0.33	0.33	0.33	0.33	0.50	1.00	1.00	5.00	3.00	3.00	**2.00**
LU	0.33	0.20	0.20	0.33	0.20	0.20	0.20	0.20	0.33	0.33	0.20	0.50	1.00	1.00	0.20	1.00	1.00	3.00	**3.00**
LO	0.20	0.33	0.33	0.20	0.20	0.20	0.20	0.20	0.20	0.33	0.33	0.33	0.33	0.33	0.33	1.00	1.00	2.00	**1.00**
HC	0.33	0.33	0.33	0.33	0.20	0.20	0.20	0.33	0.50	0.33	0.50	0.33	0.33	0.50	0.33	0.33	0.50	1.00	**2.00**
CR = 0.0922																			

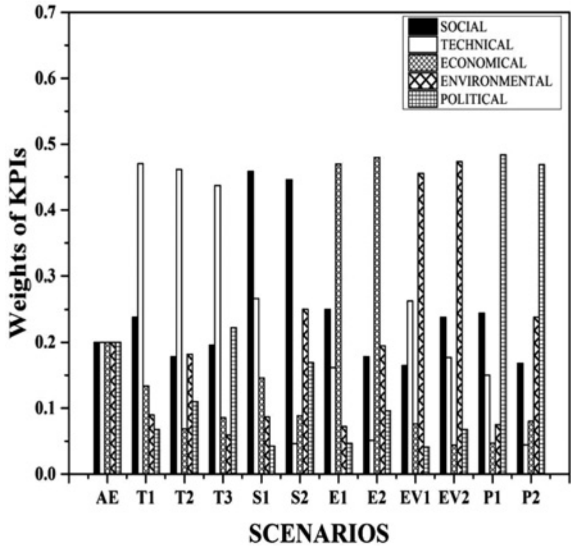

Fig. 2 *Weights of KPIs on different scenarios*

basically based on prioritisation of criteria/KPIs. For achieving a robust and real-time solution, multiple scenarios should be taken into consideration with multiple KPIs as pointed out in [11]. Hence, a total of 12 scenarios based on the priority of criteria/ KPI as illustrated in Table 3 are considered in this research work.

3 MCDA-based evaluation of alternatives

There are several decision analysis tools and software packages available in the literature which are being used in renewable energy systems such as value measurement models, outranking models, TRIPTYCH etc. [11]. An in-depth review of the recent scholarly literature has been illustrated in [11, 23]. Depending on the availability of data, KPIs, scenarios etc. and with experts advice, appropriate MCDA method needs to be utilised for the analysis as suggested in many research works [7, 21, 23, 30]. AHP is one of the best and versatile decisions-making methods given by Satty [38, 39]. Its capability to accommodate qualitative, as well as quantitative criteria/KPIs in the same framework, makes it more attractive method. Also, the consistency of the decisions taken can be verified at every instance depending upon the values of consistency ratio (CR) [38, 39]. At first, the problem is structured into a hierarchical model with three levels containing: primary objective or goal, criteria/KPIs and then alternatives to be evaluated [11, 30, 38, 39]. By performing a pairwise comparison between the level/elements of hierarchical model, i.e. criteria with criteria and alternatives on each criterion and assigning them values as per Saaty's scale [38, 39], a judgmental matrix is obtained. A program based on MATLAB is developed following the methodology available in [11, 38, 39] to determine the weights of each criterion and alternatives more efficiently. To calculate the value of CR when the KPIs is more than 15, the values of the random index are taken up from [40]. If the values of $CR < 0.1$ the consistency of decision made is satisfactory [38, 39]. Table 4 shows the pairwise comparison matrix of criteria and relative weights (W) of each criterion for scenario T1. In a similar way, the relative

Table 5 Pairwise comparison matrix (alternative × alternative)

	A1	A2	A3	A4	A5	A6	A7	A8	A9	A10	A11	A12	AW
A1	1.00	1.00	1.00	3.00	1.00	2.00	1.00	1.00	1.00	2.00	3.00	5.00	0.11
A2	1.00	1.00	2.00	5.00	1.00	3.00	1.00	1.00	1.00	3.00	3.00	5.00	0.13
A3	1.00	0.50	1.00	5.00	1.00	2.00	1.00	1.00	1.00	3.00	5.00	5.00	0.11
A4	0.33	0.20	0.20	1.00	0.20	0.33	0.14	0.20	0.17	1.00	1.00	1.00	0.02
A5	1.00	1.00	1.00	5.00	1.00	3.00	1.00	1.00	1.00	4.00	3.00	5.00	0.12
A6	0.50	0.33	0.33	3.00	0.33	1.00	0.33	0.50	0.33	3.00	2.00	5.00	0.06
A7	1.00	1.00	1.00	7.00	1.00	3.00	1.00	2.00	1.00	2.00	3.00	5.00	0.13
A8	1.00	1.00	1.00	5.00	1.00	2.00	0.50	1.00	0.50	3.00	2.00	3.00	0.10
A9	1.00	1.00	1.00	6.00	1.00	3.00	1.00	2.00	1.00	5.00	3.00	5.00	0.13
A10	0.50	0.33	0.33	1.00	0.25	0.33	0.50	0.33	0.20	1.00	1.00	3.00	0.04
A11	0.33	0.33	0.33	1.00	0.33	0.50	0.33	0.50	0.33	1.00	1.00	3.00	0.04
A12	0.20	0.20	0.20	1.00	0.20	0.20	0.20	0.33	0.20	0.33	0.33	1.00	0.02
CR = 0.0261													

Table 6 Final scores of alternatives on scenarios

	AE	T1	T2	T3	S1	S2	E1	E2	EV1	EV2	P1	P2
A1	0.116	0.101	0.095	0.097	0.112	0.116	0.143	0.105	0.105	0.106	0.104	0.111
A2	0.093	0.090	0.090	0.089	0.093	0.094	0.098	0.091	0.091	0.092	0.089	0.092
A3	0.085	0.083	0.084	0.085	0.086	0.088	0.082	0.084	0.084	0.085	0.089	0.088
A4	0.087	0.089	0.086	0.088	0.085	0.084	0.091	0.084	0.084	0.083	0.088	0.086
A5	0.074	0.082	0.082	0.082	0.080	0.077	0.068	0.075	0.075	0.075	0.078	0.074
A6	0.068	0.079	0.081	0.081	0.073	0.068	0.057	0.070	0.070	0.069	0.077	0.070
A7	0.097	0.094	0.096	0.094	0.096	0.097	0.097	0.096	0.096	0.097	0.095	0.097
A8	0.083	0.086	0.088	0.086	0.085	0.082	0.080	0.086	0.086	0.085	0.082	0.081
A9	0.080	0.091	0.092	0.092	0.089	0.082	0.072	0.082	0.082	0.081	0.085	0.079
A10	0.091	0.087	0.088	0.085	0.086	0.090	0.092	0.097	0.097	0.097	0.086	0.091
A11	0.065	0.061	0.061	0.061	0.063	0.067	0.064	0.067	0.067	0.068	0.065	0.067
A12	0.061	0.057	0.060	0.060	0.051	0.055	0.056	0.063	0.063	0.062	0.062	0.065

Table 7 Final rankings of alternatives on scenarios

Ranking	AE	T1	T2	T3	S1	S2	E1	E2	EV1	EV2	P1	P2
1st	A1	A1	A7	A1	A1	A1	A1	A1	A1	A1	A1	A1
2nd	A7	A7	A1	A7	A7	A7	A2	A10	A10	A10	A7	A7
3rd	A2	A9	A9	A9	A2	A2	A7	A7	A7	A7	A2	A2
4th	A10	A2	A2	A2	A9	A10	A10	A2	A2	A2	A3	A10
5th	A4	A4	A10	A4	A3	A3	A4	A8	A8	A3	A4	A3
6th	A3	A10	A8	A8	A10	A4	A3	A4	A4	A8	A10	A4
7th	A8	A8	A4	A10	A4	A9	A8	A3	A3	A4	A9	A8
8th	A9	A3	A3	A3	A8	A8	A9	A9	A9	A9	A8	A9
9th	A5	A5	A5	A5	A5	A5	A5	A5	A5	A5	A5	A5
10th	A6	A6	A6	A6	A6	A6	A11	A6	A6	A6	A6	A6
11th	A11	A11	A11	A11	A11	A11	A6	A11	A11	A11	A11	A11
12th	A12	A12	A12	A12	A12	A12	A12	A12	A12	A12	A12	A12

weights are determined for other 11 scenarios. Fig. 2 depicts the weights of KPIs considering 12 scenarios.

4 Results

Similarly (as illustrated in Section 3), the pairwise comparison is performed between the alternatives based on each criterion and relative weights of alternatives are obtained. An example of alternative decision matrix considering one criterion (PA) is shown in Table 5. A total of 20 alternative matrices of dimension (12×12) is constructed based on each criterion on each scenario and alternatives relative weights (AW) is obtained.

To determine the final scores of alternatives based on each criterion, matrix multiplication between the relative weights of criteria with relative weights of alternatives is done. To find the final scores based on each scenario, each time matrix multiplication of each scenario criteria weights with alternative weights has to be performed. Now depending upon the scores obtained by alternatives considering each scenarios, the final ranking is done. In Table 6, the final scores of the alternatives (A1–A12) considering each scenario (AE-P2) is given.

The rankings of the alternatives are exclusively based on the final scores obtained. For example, considering scenario AE the highest score is of alternatives A1 followed by A7 and A2. When scenario T1 is considered, the value of final scores changes even if the first ranking is being held by A1 and second by A7. However, in this case, the third rank is being taken by A9. So, all the rankings are done depending on the scores. The highest takes the first rank, second highest takes second rank and so on. Table 7 shows the ranking of the alternatives based on the final scores obtains considering the scenarios.

The first rank is mostly taken by alternative A1 (PV + battery) in 11 scenarios, and only once in scenario T2, the first rank is of alternative A7 (HRoR + PHS). A lot of variation in the ranking of alternatives can be observed in the second, third and fourth positions when different scenarios are considered. Depending upon the frequency of occurrence, alternatives A1, A7, A2, A9 and A10 hold top four positions as illustrated in Table 8.

However, the first rank depending upon the frequency of occurrence is of A1 (11 times) and the second position by A7 (7 times).

Table 8 Frequency of occurrence

	A1	A2	A7	A9	A10
1st	11	0	1	0	0
2nd	1	1	7	0	3
3rd	0	5	4	3	0
4th	0	6	0	1	4

Third and fourth rank considering all the scenarios is shared by alternatives A2, A10, and A9, respectively.

5 Conclusion

In this work decision analysis-based tool, AHP is utilised successfully to design a rural microgrid considering multiple criteria with various scenarios. The results obtained show that the final score and thus ranking of the alternatives is not similar for all the scenarios. A set of solutions are obtained depending upon different scenarios considering similar criteria's.

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7 References

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