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# An integrated design approach for rural electrification based on community microgrids

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## ABSTRACT

This work aims to illustrate a sustainable socio-techno-economic microgrid (SSTEM) design framework based on locally accessible energy resources such as solar, wind, hydro, etc. for remote/rural electrification purposes in the context of developing and least developing nations. The proposed SSTEM framework consists of separate three sub-design levels integrated as one all-inclusive design process. The outlined framework can incorporate several combinations of the available energy resources in the vicinity such as hydrokinetic system (HKS), photovoltaic (PV), small wind turbine (SWT), etc. as primary energy sources with pump hydro system (PHS) and battery as energy storage and diesel generator as a backup for designing the community microgrid. Many combinations of primary generating sources and storage systems are utilized in this study to determine the suitable alternative. A preliminary socio-techno-economic evaluation of different microgrid elements (energy technologies and storage systems) will be introduced in this first stage of the proposed design process using decision analysis tools based on a set of performance indicators. The best alternatives from each of the elements, i.e., renewable energy technologies (RETs) and energy storage systems (ESS) assessed on the anticipated performance indicators, will be obtained to be used for the next-level design process. In the subsequent design stage, the detailed feasibility (techno-economic) analysis of the solutions by combining different elements (RETs and ESS), which are obtained after the first stage with diesel generator (DG) in different microgrid architectures will be performed with multi-objective optimization tool. Different sizes and costing of various microgrid elements in varying suitable architectures will be obtained after this stage. In the final stage multi-criteria decision making (MCDM) models will be utilized to determine the best possible microgrid based on suitably defined criteria for electrifying the remote villages/communities.

**Keywords:** Renewable energy, community microgrids, rural electrification, sustainable development, multi-criteria decision making, socio-techno analysis.

## 1. INTRODUCTION

Energy access and energy security are significant factors that directly affect any country's economic, social, and environmental sustainability [1, 2]. Energy is indispensable for the development of any country, region, and its people. That is why in 2015, 193 countries adopted a common goal as a part of United Nations Sustainable Development Goals (SDGs) in order to ensure cheap, reliable, and sustainable energy access to all by 2030 [3, 4]. The falling cost of clean energy technologies and their rapid development has contributed significantly to energy access, especially in developing countries, but it is challenging to keep pace with their population growth, such as in sub-Saharan Africa [4]. For clean cooking access, only a little progress has been achieved in developing and least developed nations. Nevertheless, 2.651 billion people, i.e., 38 % of the World population in 2018, have no access to clean cooking capability out of which 2.37 billion still rely on biomass sources [2, 4]. The electricity access condition improved in 2018 with 950 million without access compared to 1.7 billion in 2000, and it is anticipated to decline to 0.67 billion by 2030 [2, 4]. In developing Asia itself, 1.674 billion people have no access to clean cooking, with 1.46 billion relying on traditional sources such as firewood, dung cakes, etc. until 2018 [2].

One of the major emerging economies, India has made significant progress with an electrification rate of 95 % providing access to more than 80 % of its population but still, 51% of its people suffer from the access to the clean cooking facility [2]. China alone has shown tremendous progress in achieving 100 % electrification, yet in 2018, 28 % (399 million) of its population currently does not have any access to clean cooking with 242 million relying heavily on traditional biomass for heating and cooking purposes [2, 5, 6]. Most of the population in developing and least developed countries who do not have access to clean cooking and electricity is constituted in remote and rural locations [5, 7].

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As of 2015, there were more than 18,000 villages that do not have aces to electricity in India. This condition become even worse in the case of the North-eastern region (NER) [7, 8]. The whole NER suffers from poor road infrastructure, challenging terrain having a majority of areas covered by mountains and forest which are few major causes of its under development and poor energy access [9]. In such type of regions, it is difficult to provide electricity access through the grid, which suffers from frequent outages due to transmission line breakage caused by the landslide in mountain regions [9, 10] and thus, off-grid/stand-alone energy solutions based on the locally available resources are best suitable for such areas [11-13]. Several research studies exist in the literature on isolated microgrid design for remote locations utilizing the local energy sources [12, 14-19].

Authors in [20-22] have used decision analysis to obtain suitable energy system alternatives with traits aligned with sustainable development. Akinyele and Rayudu [19] have illustrated a design study based on the feasibility analysis of a PV based system for a community in Nigeria. Kusakana in [23] has presented an isolated hybrid microgrid design based on combinations of HKS, DG, and PHS for a rural community in South Africa. Using the HOMER software hybrid energy system with HKS and PHS has been investigated in [24]. Several other studies based on single objective linear [25] and multiple objective optimization model [26-28] based on RETs for rural areas have been reported in the literature. However, most of the studies outlined in literature are concentrated on the sizing and costing of energy systems either using some well-known software tools such as HOMER (free limited version), which is straightforwardly applied or based on optimization models. Moreover, for design analysis, random selection of RETs and storage system has been done without considering its commercial viability, suitability, social aspects and increased load demand for specified locations, often leading to complete project failures [9, 29].

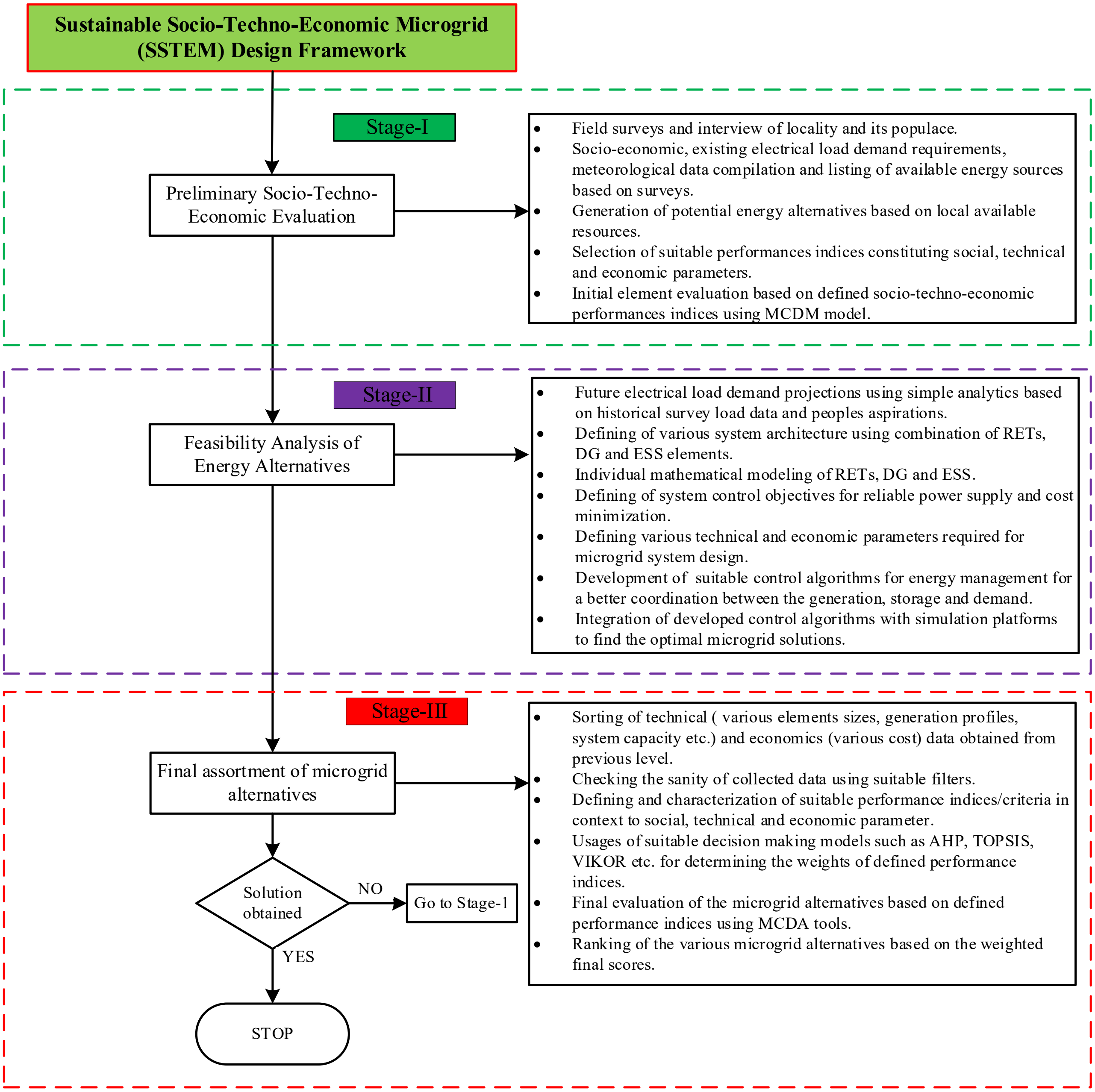
Hence, this study proposes a novel SSTEM framework with the synergies of the decision analysis model and optimization tool for remote/rural electrification purposes for developing and least developed nations. The community microgrid design is based on the suitable combination of locally available and commercial feasible energy resources (in the case study HKS, SWT, PV) with PHS and BSS as storage and DG as back up. Analytical hierarchal process (AHP) and Technique of Order Preference Similarity to the Ideal Solution (TOPSIS) decision analysis models, as iterated in [30] are utilized for preliminary level design. For the second level design, a load-following economic dispatch (LFED) strategy using a benchmark microgrid design optimization tool developed by HOMER LLC, USA (full commercial version) [31] with required mathematical modelling will be carried out. Finally, the best design will be selected using a hybrid decision analysis tool (AHP + TOPSIS). When implemented, the proposed framework will provide a set of judgmental solutions for electrification based on socio-cultural, geographical and economic aspects of a particular location or region.

## 2. PROPOSED SSTEM FRAMEWORK

Figure 1 illustrates the detailed block diagram of the proposed SSTEM design process for rural electrification purposes. It consists of majorly of three different stages having several sub-design tasks integrated into one comprehensive design process. **Stage-I** deals with the preliminary socio-techno-economic evaluation of the target vicinity to determine suitable alternatives for microgrid design. It incorporates field surveys and interviews to understand the peoples' perceptions, aspirations, and responses towards energy technologies. This will help to clearly understand their requirements and expectations from the energy project, which has majorly been neglected in the available microgrid design processes in the literature so far. Once the community's detailed social profiling is done, suitable social performance indicators such as public acceptance, public health, etc. will be listed for evaluating the available energy resources to be used for microgrid design [7, 32]. Similarly, suitable technical indicators (such as power output, scalability, etc.) and economic indices (initial capital costs) for RETs, DG, and battery storage will be taken for preliminary evaluation using decision-making models such as AHP, TOPSIS, etc. [33].

Once the preliminary evaluation is completed, a set of solutions will be obtained, which will serve as input to the subsequent stage of the proposed process. **Stage-II** exhibits the detailed feasibility analysis of the energy alternatives in different microgrid architectures considering future electrical load demand growth. The simple analytical method illustrated in [34] is utilized for demand projections. The detailed individual component modeling with varying storage systems with the formulation of objective function and values of various parameters is adopted from [32, 35]. The control dispatch algorithm is formulated in MATLAB and then integrated with a complete commercial version of benchmark microgrid design tool HOMER PRO [31] to run simulations to find optimal microgrid solutions in different architectures. All the varying elements sizes (RETs, DG, and storage system), along with their cost value, should be recorded.

In the final **stage-III**, of the design process, all the data (costing and sizing) of various microgrid solutions obtained from the previous stage, is analyzed for sanity. Once the data sort is completed, suitable performance indices considering social, technical, and economic parameters are defined and characterized for final



- Field surveys and interview of locality and its populace.
- Socio-economic, existing electrical load demand requirements, meteorological data compilation and listing of available energy sources based on surveys.
- Generation of potential energy alternatives based on local available resources.
- Selection of suitable performances indices constituting social, technical and economic parameters.
- Initial element evaluation based on defined socio-techno-economic performances indices using MCDM model.

- Future electrical load demand projections using simple analytics based on historical survey load data and peoples aspirations.
- Defining of various system architecture using combination of RETs, DG and ESS elements.
- Individual mathematical modeling of RETs, DG and ESS.
- Defining of system control objectives for reliable power supply and cost minimization.
- Defining various technical and economic parameters required for microgrid system design.
- Development of suitable control algorithms for energy management for a better coordination between the generation, storage and demand.
- Integration of developed control algorithms with simulation platforms to find the optimal microgrid solutions.

- Sorting of technical ( various elements sizes, generation profiles, system capacity etc.) and economics (various cost) data obtained from previous level.
- Checking the sanity of collected data using suitable filters.
- Defining and characterization of suitable performance indices/criteria in context to social, technical and economic parameter.
- Usages of suitable decision making models such as AHP, TOPSIS, VIKOR etc. for determining the weights of defined performance indices.
- Final evaluation of the microgrid alternatives based on defined performance indices using MCDA tools.
- Ranking of the various microgrid alternatives based on the weighted final scores.

Fig. 1 Proposed SSTEM Design Framework for Rural Electrfication

evaluation as outlined in [36]. Utilizing suitable MCDA models such as AHP, Fuzzy-AHP the weightage of all the defined indices are determined. Then using TOPSIS or VIKOR model, the optimal microgrid solutions having different architectures are finally evaluated and raked according to their weight score. After the completion of the final stage, ranking of microgrid alternatives are obtained. Depending upon the ranking, the final microgrid alternative is chosen. When implemented, this framework generates a number of judgmental solutions in nature and depending upon the preferences of the community populace and expert advice, the microgrid alternative should be selected for electrification.

## 3. CASE STUDY

This study's target village is located in the North-Eastern part of India in East Kameng Region (EKR). Tajo village comes under Chyangatajo circle, which has more than 35 similar rural communities. Only 15 have been electrified as per March 2017.

### *3.1 Preliminary Socio-techno economic evaluation*

Tajo village has 20 households with a total population of 158 with an average family size of 5-6 people [37]. The majority of the population in the whole region falls under below the poverty line (BPL) with an annual income of INR 30,000 (USD 500 approx.). Their livelihood is dependent on agriculture (mountain farming) and fishing [32]. The whole

EKR has an average annual rainfall of 1977-2400 mm [38] with a heavy rainy season for almost 6-7 months having an annual solar irradiance of 3.91 kWh/m$^2$/day and an average annual wind speed of 3.98 m/s respectively [39]. The village is located close to the river stream of the Pachi and Para river, which has approximate average water in between 3.79-4.29 m/s [40]. Based on the field surveys in different seasons, the community load demand was generated which is constituted of 20 households as illustrated in Figure 2.

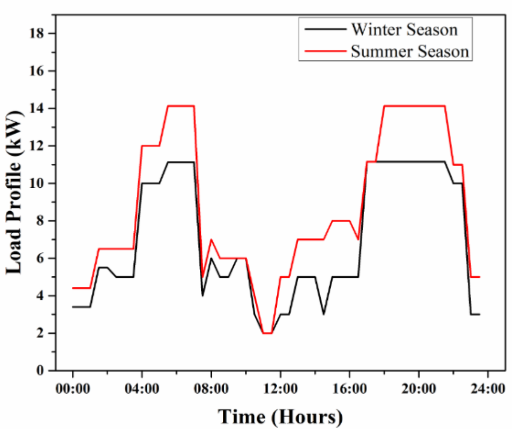


Fig. 2 Seasonal load profile of Tajo Village

Based on the field surveys, local market surveys, interviews with community leaders, and expert advice from power entities in the EKR region, alternatives based on a combination of RETs (HKS, SWT, PV), ESS (battery and PHS) along with DG were taken up for preliminary analysis. As mentioned in the Stage-I of SSTEM design framework, **initial social analysis** of RETs, ESS, and DG using decision-making model AHP based on the specific four social performance indices as outlined in Table 1 is carried out.

Table 1. Social Performance Indices (SPI) for Technology Selection

| Indices/criteria | Description | Weights using AHP |
|---|---|---|
| Public acceptance (PA) | Acceptance of energy project by the community populace. | **0.3989** |
| Populace Health (PH) | Effect of technologies on public health in direct or indirect ways. | **0.1607** |
| Employment opportunities (EO) | Generation of any potential employment or business opportunities due to change in the energy access situation of the vicinity. | **0.0832** |
| Public Perception (PP) | Public knowledge, familiarity, and understanding of the various technologies used in the design of energy project. | **0.3572** |

All available energy generation technologies (EGT) and storage technologies (ST) are evaluated based on the SPIs to discard the worst technology in context to the social requirements of the community. As shown in Table 2 in red highlighted, SWT has the lowest weight and ranks worst on SPIs; hence it is not used as potential EGT for designing the energy system. Similarly, using MCDM model (AHP and TOPSIS), the preliminary techno-economic analysis based on defined criteria is carried out for selecting suitable commercially available RETs (HKS, PV) and battery storage system (BSS). A total of 8 lead-acid battery models with different capacities, nominal voltage life cycle, etc. are considered for evaluation.

Table 2. Evaluation Matrix for Technology Selection using MCDM

| **EGT & ST** | **Social Performance Indices (SPI)** | | | | **Final weights of various technologies** |
|---|---|---|---|---|---|
| | ***PA*** | ***PH*** | ***EO*** | ***PP*** | |
| ***HKS*** | 0.2852 | 0.2957 | 0.235 | 0.1777 | **0.24431** |
| ***SWT*** | 0.0901 | 0.1057 | 0.1362 | 0.1171 | **0.10609** |
| ***SPV*** | 0.1685 | 0.1876 | 0.16 | 0.1888 | **0.17811** |
| ***DG*** | 0.1029 | 0.0517 | 0.1154 | 0.161 | **0.11647** |
| ***BSS*** | 0.2275 | 0.2162 | 0.1934 | 0.1999 | **0.21299** |
| ***PHS*** | 0.1259 | 0.1431 | 0.16 | 0.1555 | **0.14207** |

Further, 7 HKS turbine models and 16 PV models from the local market are considered based on their power rating, cost, weight, etc. A 5 kW Smart Monofloat scalable HKS system from Smart Hydro Power [41], Somera Prime monocrystalline-72cell-60-310Wp series PV from Vikram Solar [42], and 12VRE-3000 tubular flooded lead-acid battery from Discover Energy Corporation [43] are selected. The PHS design is site-specific and not commercially available. Its proper sizes can only be obtained after feasibility analysis. Hence, PHS is not included for preliminary techno-economic assessment in Stage-I.

### *3.2 Feasibility Analysis of energy alternatives*

Various elements based on the earlier socio-techno-economic evaluation of EGTs and SS are selected to generate potential energy alternatives. Six energy alternatives in different architectures having a combination of EGTs and SS are listed in Table 3.

Table 3. List of energy alternatives for microgrid design

| Sl.no | Energy Alternatives with different EGT and SS |
|---|---|
| 1 | PV+HKS+BSS (MG1) |
| 2 | HKS+DG+BSS (MG2) |
| 3 | PV+HKS+DG+BSS (MG3) |
| 4 | PV+HKS+PHS (MG4) |
| 5 | HKS+DG+PHS (MG5) |
| 6 | PV+HKS+DG+PHS (MG6) |

The detailed mathematical modelling of various elements of energy alternatives is done based on the individual technical datasheets for PV [42], HKS [41], DG [44] and BSS [43], respectively. The PHS modeling is carried out with reference to our previous work [32] with changes in site-specific technical and economic parameters. Power dispatch control algorithms with overall system cost minimization are developed in MATLAB and is integrated with HOMER PRO, as illustrated in [9, 35] to perform the detailed feasibility analysis. Different component sizes of the energy alternatives are obtained, as shown in Table 4. Similarly, different cost values (net present, capital, O & M, and cost of electricity) are obtained as shown in Figures 3 and 4.

Table 4. Final component size of various microgrid energy alternatives

| Microgrid Energy Alternative | Technical Results (Component Size) | | | | | | |
|---|---|---|---|---|---|---|---|
| | PV (kW) | HKS/5kW (Unit) | DG (kW) | Converter (kW) | BSS (Numbers) | PHS (kWh) | RF (%) |
| MG1 | 105 | 1 | 0 | 30 | 180 | 0 | 100 |
| MG2 | 0 | 3 | 20 | 25 | 60 | 0 | 63.5 |
| MG3 | 65 | 2 | 16 | 30 | 100 | 0 | 89.9 |
| MG4 | 100 | 1 | 0 | 0 | 0 | 441 kWh | 100 |
| MG5 | 0 | 2 | 20 | 0 | 0 | 245 kWh | 61.7 |
| MG6 | 70 | 1 | 16 | 0 | 0 | 196 kWh | 95.7 |

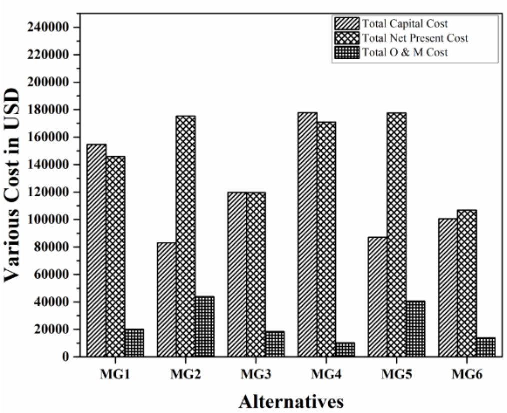


Fig. 3 Comparative illustration of various cost

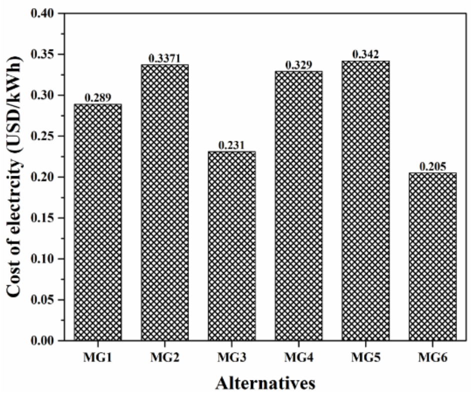


Fig. 4 Comprative illsutartion of COE of alternatives

If we compare the results illustrated in Table 4, Figures 3 and 4, it is difficult to determine the best system for the microgrid design. MG3 has the lowest costs (COE, net present, capital, and O & M) but the RF fraction and system size are lower as compared to MG1 and MG4. All the alternatives are capable of meeting the current as well as future load demand effectively. But it is not comfortable to choose one over another.

### *3.3 Final assortment of microgrid alternatives*

All the technical and economic data obtained from previous stage analysis are sorted and checked thoroughly for any discrepancies. Suitable criteria for the final assortment of microgrid alternative are defined based on the community requirements with expert advice and their relative weights are determined as illustrated in Table 5.

Table 5. Criteria and relative weights sing AHP

| Criteria final assortment of microgrid alternatives | Final Relative Weights (FRWc) |
|---|---|
| Total Capital cost (FC1) | **0.2294** |
| Total NPC (FC2) | **0.3252** |
| Total O & M (FC3) | **0.1146** |
| Cost of Electricity (FC4) | **0.14** |
| Renewable Fraction (FC5) | **0.1907** |

Once the relative criteria weights are determined, using TOPSIS method [33, 36] the microgrid alternatives are evaluated, and their final weight score is recorded as shown in Table 6.

Table 6. Final weight score and rankings of microgrid alternatives

| Microgrid Alternatives | Final weight score | Final Ranking |
|---|---|---|
| MG1 | 0.5854 | 2nd |
| MG2 | 0.5487 | 5th |
| MG3 | 0.5488 | 4th |
| MG4 | 0.5439 | 6th |
| MG5 | 0.5533 | 3rd |
| MG6 | 0.5917 | 1st |

The microgrid alternative (MG6) with the highest weight score is ranked 1st followed by MG1 and MG5. Alternative MG6 is most suitable for electrifying the target village.

## 4. CONCLUSION

The proposed framework outlined in this manuscript describes a simple and very effective method combining the synergies of decision analysis and multi-objective optimization to find a realistic solution for electrifying the remote communities of developing nations. The efficacy of the design process is illustrated with the help of a case study for electrifying a remote village. A set of microgrid solutions are obtained from this analysis as observed from case study results, which are robust and economical. The notions presented in this paper will be helpful in electrifying similar remote locations. In future work, the design process will be extended to accommodate environmental and institutional traits as well with a large number of scenarios to show the trade-off between choices made clearly with a comparative analysis for differing geographical locations. Further, a new predictive control algorithm for power management will be developed and accommodated in the design process to handle the abrupt changes in load demand due to unprecedented events.

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