IEEE Access
Multidisciplinary ⋮ Rapid Review ⋮ Open Access Journal

Received March 25, 2018, accepted April 25, 2018, date of publication May 2, 2018, date of current version May 24, 2018.

Digital Object Identifier 10.1109/ACCESS.2018.2832460

A Novel Methodological Framework for the Design of Sustainable Rural Microgrid for Developing Nations

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ABSTRACT Sustainable electrification planning for remote locations especially in developing countries is very complex in nature while considering different traits such as social, economic, technical, and environmental. To address these issues related to current energy needs depending upon the end user requirements, a coherent, translucent, efficient, and rational energy planning framework has to be identified. This paper presents a comprehensive generalized methodological framework based on the synergies of decision analysis and optimization models for the design of a reliable, robust, and economic microgrid system based on locally available resources for rural communities in developing nations. The framework consists of three different stages. First, decision analysis considering various criterions (technical, social, economic, and environmental) for the selection of suitable energy alternative for designing the microgrid considering multiple scenarios are carried out. Second, the optimal sizing of the various energy resources in different microgrid structures is illustrated. Third, hybrid decision analysis methods are used for selection of the best sustainable microgrid energy system. Finally, the framework presented is then utilized for the design of a sustainable rural microgrid for a remote community located in the Himalayas in India to illustrate its effectiveness. The results obtained show that decision analysis tools provide a real-time solution for rural electrification by binding the synergy between various criteria considering different scenarios. The feasibility analysis using proposed multiyear scalable approach shows its competence not only in determining the suitable size of the microgrid, but also by reducing the net present cost and the cost of electricity significantly.

INDEX TERMS Microgrid, hybrid energy system, renewable energy, rural electrification, multi-criteria decision analysis (MCDA).

I. INTRODUCTION

According to International Energy Agency (IEA), over 16% (1186 million) of the global inhabitants do not have access to electricity. Around 53.28 % (632 millions) of which are being located in Sub-Saharan Africa with an electrification rate of 35 % (urban 63 %, rural 19 %) and 20.60 % (244 million) are in India with an electrification rate of 81% (urban 96 %, rural 74 %) [1], [2]. Moreover, over 37 % (2.7 billion) people globally rely on unclean traditional energy sources (kerosene, charcoal, biomass, dung cakes, firewood, husk, solidified crop waste, etc.) to meet their primary energy needs of lighting, cooking and heating etc. which has a significant impact on the environment as well as their health [3]–[5]. Approximately, four million people die each year in developing nations due to the inept burning of solid fuels in ineffectively ventilated houses mostly women and children from respiratory diseases, cardiovascular diseases, cancer, burns and poisoning [6], [7]. More than 80 % of these inhabitants are concentrated in the rural and remote areas with no access to clean energy [2], [4], [8]–[13]. In India itself till April 2015 approximately, 18452 un-electrified villages existed out of which 14326 villages have been electrified till August 2017. Still, 3139 villages need to be electrified by 2017 as the target set by Rural Electrification Corporation (REC), Ministry of Power, Government of India [14].

Energy demands are projected to grow in developing countries especially in Sub-Saharan Africa by 2040 due to large population growth [2]. Also, in the case of Asia specifically India and China; the energy demand growth is projected to rise mainly due to their overall development goals such as infrastructure and industrial development, transportation, commercialization, agricultural production, etc. Surplus energy is the main key to help India and China to achieve their development goals [1], [2]. Globally, 48 % rise in energy demand is expected by 2040 most of which is going to occur in non-OCED (Organization for Economic Cooperation and Development) nations with strong and long-term economic growth such as India and China [15], [16]. Despite a great achievement to become 100 % electrified nation by 2015, China still struggles to provide a solution for clean energy to cook and better sanitation to around one-third of its people in rural areas showing a disconnect which may occur between rising income, better electricity access, and clean cooking facilities [2], [17]. There seems to be a very tough challenge technically, socially, economically and environmentally for the fast-growing economies of the World to provide a quality-based and affordable modern energy to its people. Although nuclear energy has great potential to generate vast amounts of power, there is a significant question mark in its economic and environmental sustainability [18]. Use of green renewable energy resources can not only play a major role in the development of emerging economies, but it can also help to eradicate the issues associated with global poverty, surplus food production, public health improvement, education and better sanitation [7], [18]–[21]. Universal access to modern energy needs with a perspective of sustainability can only be achieved by having improved and efficient use of sustainable rural electrification.

Sustainable rural electrification due to the inclusion of various stakeholders has become very complex in nature. A proper and efficient planning methodology is needed for successful implementation of rural electrification based on locally available renewable energy sources. Herington *et al.* [22] have presented a critical review of literature published over 35 years to explore the various models, practices, and progress made in the context of rural energy planning in both developed and developing economies. The authors strongly point out the flaw by energy planner for not providing necessary attention to include the social and political factors while designing energy systems. With respect to the developing world, various business models and barriers related to private sector participation in microgrid based rural electrification projects have been discussed in [23]. Palit and Bandyopadhyay [24] have provided a comparative analysis considering the role of grid and off-grid system for rural electrification purposes in South Asia based on their function, cost of supply, socio-economic benefits, technical challenges and their impacts locally. Palit and Bandyopadhyay [24] pointed out clearly that rural electrification projects are complex in nature and a balanced approach based on demand and supply side management should be followed to harness locally available renewable energy sources with a sustainable approach. The existence of unreliable grids in developing nations such as in East Africa is one of the major factors to justify the use of off-grid centralized energy systems [16], [25]. Even grid or off-grid based project is solely not dependent on technologies but also the government policies. Hence, a proper synergy between all the stakeholders must be followed for successful implementation of the electrification project [24]. Rojas-Zerpa and Yusta [26] have examined various mathematical models and technologies present in literature being used for electrification planning for remote localities in decentralized configurations. The energy supply system is a multidimensional mathematical problem with multiple criteria and multiple objectives in nature [27], [28]. A specific indication regarding the advantages and applications of multicriteria decision-making models (MCDM) in energy alternative selection or the configuration of the energy system (centralized/decentralized) has been pointed out [26]. Proper attention to the end user and its significance in the success of energy projects for remote locations based on local values has been made by Hirmer and Cruickshank [29]. A theoretical framework to improve electricity access in developing nations using a mini-grid /micro-grid in isolated configuration is shown in [8], [30], and [31]. Using MCDM and goal programming (GP) techniques, a sustainable planning methodology for Gulf countries has been outlined in [32]. A global model for rural electrification to improve the household electricity needs in developing countries is presented in [33]. The global application model is based on econometric analysis firstly to determine the rate of electrification and secondly the cost involved. Various policies, models, and frameworks have been reported in the literature in context to rural energy planning over the years [4], [5], [8], [22], [24], [26], [33]–[42].

In most of the rural energy planning methods available, environmental and social considerations have been poorly explored or neglected, due to which many project failures have been reported in the literature [3], [4], [17], [19], [28], [29], [43]. Even with the existence of many government initiatives and schemes for rural electrification in developing countries, the energy needs of people cannot be met as the majority of the schemes are more concerned about the numbers than real benefits [44]. A detailed techno-financial design of electrification projects in rural and remote location to determine the cost-effective and reliable energy system is reported in [35] and [45]–[70]. In the literature, following main problems remain which must be addressed to obtain a robust, reliable and cost-effective energy system with a perspective of sustainable development [4], [8], [19], [23]–[26], [30], [34], [36], [44], [54], [55], [71]–[78]:

i) Ignorance of socio-cultural aspects causing failures to the energy projects.
ii) Negligence of user values while energy planning.
iii) Biased and random selection of energy alternative and configurations for project design and analysis.
iv) No account of yearly electrical load growth while developing the power system thus leading to a huge error in the calculation of various involved costs.
v) No use of benchmark costs from the government regulated organizations for the cost analysis. Most of the studies completely ignore the land cost, civil work cost, labor cost, etc.

Keeping all the above problems and recommendations laid down in the literature by various scholars, a detailed and comprehensive methodological framework combining decision analysis and optimization tool considering a yearly load growth approach to develop a sustainable rural microgrid is presented in this paper. The framework presented is simple in nature and can be implemented for rural electrification purposes for developing nations. The paper is organized as follows. Section II provides the detailed description of the proposed methodological framework. Section III illustrates the effectiveness of the proposed framework with a case study taken from a remote village in the Himalayas along with the detailed results. Section IV finally concludes the paper.

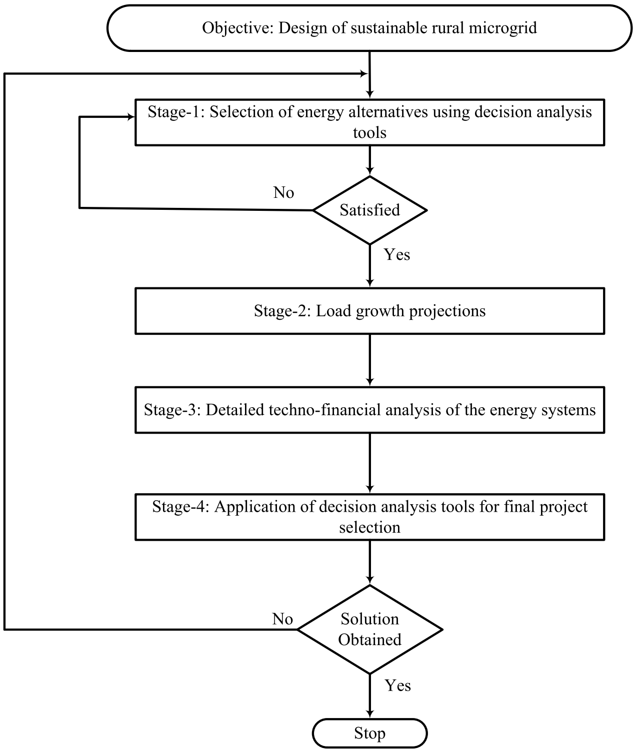


FIGURE 1. **Proposed methodological framework for sustainable microgrid design.**

II. METHODOLOGICAL ASPECTS

Figure 1 illustrates the proposed generalized framework for designing a sustainable rural microgrid for developing nations. The methodological framework consists of four different stages as shown in Figure 1. Stage-1 is the preliminary stage dealing with the selection of energy alternatives by utilizing the decision analysis tools. Once the preliminary set of energy alternative solutions are obtained, load growth projections will be carried out in stage-2 followed by the cost-effective sizing of various components considering different microgrid architectures at stage-3 respectively. A number of microgrid solutions will be obtained after the stage-3 having different cost and size. Finally at stage-4 by utilizing the decision analysis tools, the ranking of the microgrid solutions will be done which provides a set of solutions which are judgmental and depending upon the views of decision makers/ experts the final selection can be made. Mostly, the framework developed is user-friendly, and this iterates a practical preliminary design. The detailed explanation of the methodology as illustrated in Figure 1 has been provided in the following sub-sections.

A. STAGE-1: SELECTION OF ENERGY ALTERNATIVES USING DECISION ANALYSIS TOOLS (FIGURE 1 AT STAGE-1)

It has been already outlined in the introduction section I that sustainable rural electrification is a multidimensional problem with multiple objectives and many traits [26]. The involvement of multiple stakeholders, benchmarks, and the inclusion of more green renewable sources in rural electrification system has made the design process more difficult [28], [43]. Various MCDM models have been used for energy planning for electrification purpose to attain sustainability. A recent detailed review of such models and along with their application has been illustrated by authors in [28] and [79]–[91]. Figure 2 shows the process of selection of energy alternatives using multi-criteria decision analysis (MCDA) tools.

At first, the survey of the target location is carried out to collect the various data (load demand, local energy resources, socio-economic profile, grid data, etc.). Depending upon the locally available resources and with the help of expert advice (academicians, industrialist, practitioner, government organization, project investors, NGOs, etc.), a possible list of energy alternatives considering single or multiple resources in the isolated or grid connected system is then generated for further evaluation. Also, suitable indicators for evaluating the alternatives depending upon the availability of data, expert advice, and available literature in context to rural electrification [3], [92]–[96] has to be carried out.

Using commercially available software packages based on decision analysis tools such as Triptych or Expert Choice [28] or MCDA technique such as analytical hierarchical process (AHP), the criteria weights could be determined. A detailed review of available software tools based on MCDA has been outlined in [28]. Based on the available data collected and nature of problems along with practical consideration appropriate decision analysis method needs to be selected for further evaluation to rank the energy alternatives as stated in [43] and [88]–[91]. For evaluating the

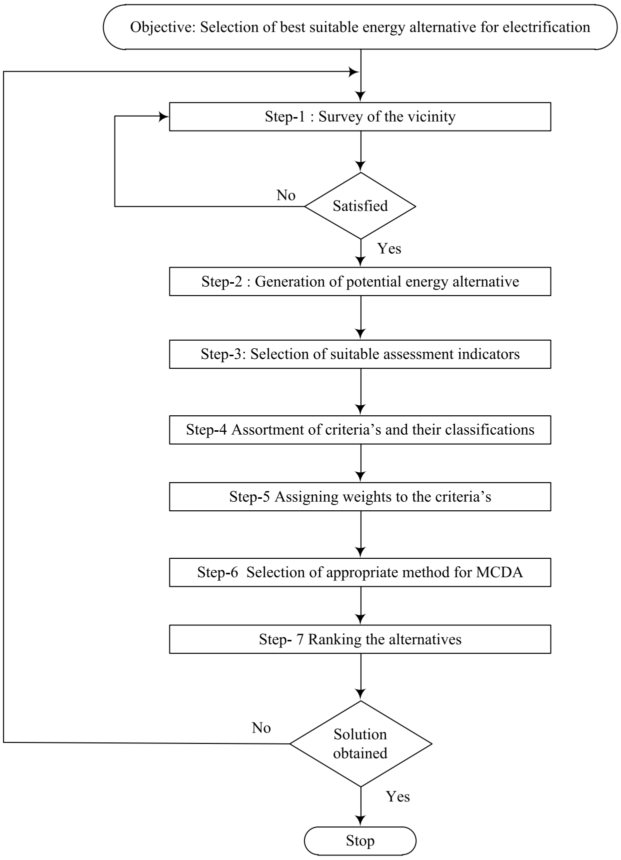


FIGURE 2. Illustration of process for preliminary selection and sustainable assessment of energy alternatives (source: author [43] with permission from the publisher).

alternatives on the defined performance indicators help from experts as well as various reports from government regulating authorities should be referred. The results obtained after the process as illustrated in Figure 2, will generate a set of solutions having different final weights and depending upon those the alternatives can be ranked. The set of outputs obtained are judgmental in nature, and by considering the expert advice (the government entities, project planners, engineers, etc.) familiar with the target locality either single or, multiple solutions should be considered for further analysis. In some instances, if the solution obtained is not realistic or satisfactory, the whole process can be repeated which will yield a different set of solutions with different weights depending upon the selected criteria's. The detailed explanation of the overall process for selection of energy alternatives as shown in Figure 2 with the aim of sustainability has been illustrated by Kumar *et al.* [43]. Also, the selection process is illustrated in this work with a case study detailed in sub-section III.B.

B. STAGE-2: LOAD GROWTH PROJECTIONS (FIGURE 1 AT STAGE -2)

Energy planning without considering future demand forecast may lead to subsequent project failures. Only a handful of studies exist in the literature that accounts for the yearly load growth [97]. Most of the works available in academic outcomes have used the current loads and have performed the design and analysis of the energy system over the project lifetime [35], [45], [46], [49]–[52], [55], [56], [98]–[106]. In such scenarios, the system will be not able to supply the demand not only causing technical issues but also financial errors leading to project failures [97]. A large number of methods and models have been reported in the literature to forecast the annual energy demand. Few of the models present in previous scholar works are simple in nature such as growth rate model using simple indicators, trend analysis models, etc. and some complex advanced models such as econometric models, engineering-economic models, etc. [41], [107]. For electrical load demand forecast, some sophisticated and complex models based on the soft computing techniques have been reported in [108]. Kandila *et al.* [109] have outlined several models such as qualitative, quarantine, time-series, stochastic, etc. for long term load projections. Akinyele and Rayudu [97] have used a 1% annual load growth to evaluate a solar photovoltaic (PV) based power system for a remote community in Nigeria considering the load growth based on the increase in the user demand data due to increase in the number of houses. However, when these models are applied at the disintegrated and remote levels, usages of such models can make things more complicated. However, simple approach as outlined by Bhattacharyya [41] can be utilized for electrical load projections for the design of energy systems for rural communities which is given in equation (1):

$$D_t = D_0(1+g)^t \tag{1}$$

where, D_t = Electrical Load demand in year t; D_0 = Electrical load demand in a year of the base year i.e. the current load; g = assumed growth rate; t = time in years.

The assumed growth rate can be derived using historical electrical load data available or can be derived using the increase in a number of consumers and rise in the economics of the targeted community as both are directly related to the demand growth [41]–[43], [97], [110]. Sometimes the availability and the quality of the historical data is also an issue, in such cases expert advice for considering the growth rate can be taken.

C. STAGE-3: DETAILED TECHNO-FINANCIAL ANALYSIS OF ENERGY SYSTEM (FIGURE 1 AT STAGE-3)

To avoid the energy project failures caused mostly due to improper sizing of the various components of the power system and for efficient utilization of renewable energy technologies (RETs), detailed technical as well as financial analysis is mandatory. Economic analysis is beneficial in determining the various costs involved such as capital, operation, and maintenance (O & M), cost of electricity (COE), etc. which are very necessary to attract the possible investors for the energy project. Due to increase in the complexity of energy planning, optimization methods have evolved from single objective to multiple objective optimizations and also to software packages. Single objective optimization based financial analysis for a hybrid energy system based on RETs for a local community is reported in [111].

Authors in [112]–[121] have provided an in-depth review of various optimization methods and computer tools for detailed technical and economic analysis applicable to RETs based sustainable energy projects. Sinha and Chandel [122] have presented a critical study regarding 19 software packages such as HOMER, Hybrid2, RET Screen, iHOGA, INSEL, TRNSYS, iGRHYSO, etc. utilized for the sizing and economic analysis of energy systems based on RETs. The use of such software tools has made the techno-economic analysis very simple and yet very useful. Recently, HOMER (Hybrid Optimization of Multiple Energy Resources) has gained much popularity for cost-efficient and reliable microgrid design based on RETs. Many studies have been reported in the literature based on the use of HOMER for the development of microgrids for the rural locations [35], [50]–[52], [59]–[70], [102]–[104], [106]. So, depending upon one's feasibility and on the counsel of experts, any of the optimization methods and models or software tools outlined in [58], [112]–[115], and [122]–[126] can be used for the full cost-effective sizing of the energy system. The specific details regarding the various architecture, RETs, and storage options being utilized in the design of rural microgrid has been reported in [127]–[130].

Many times the sizing of the components is big if considering a yearly load growth and so the upfront cost also becomes higher. So to efficiently utilize the RET's and other components and to avoid over or under sizing of the system, a very simple approach is presented in this study. The proposed method can be utilized to perform the techno-financial analysis using any of the optimization models [112]–[115], [118]–[120] or software tools already mentioned. The proposed multiyear scalable approach for carrying out techno-financial analysis is shown in Figure 3 and its detailed explanation is given below:

Phase 1 (Electrical Load Demand Calculations): Calculate the electrical load demand on a yearly basis using Equation 1 (sub-section II.B.) for all the years till the assumed project lifetime.

Phase 2 (Selection of Energy Alternatives): Choose the various energy alternatives using the methodology illustrated in sub-section II.A, Figure 2.

Phase 3 (Selection of Microgrid Architecture): Depending upon the expert advice (mainly from the government or private power generation, transmission, and distribution organization) and based on available literature decide suitable microgrid architectures for further analysis [127], [128], [130], [131]. Different microgrid architectures considered in this study for implementation of the methodology is shown in Appendix.

Phase 4 (Approximation of System Size): Using the projected electrical load data of the final year, calculate the approximate size of the system which should be able to satisfy the demand growth of all years. Note down the sizes of the various components.

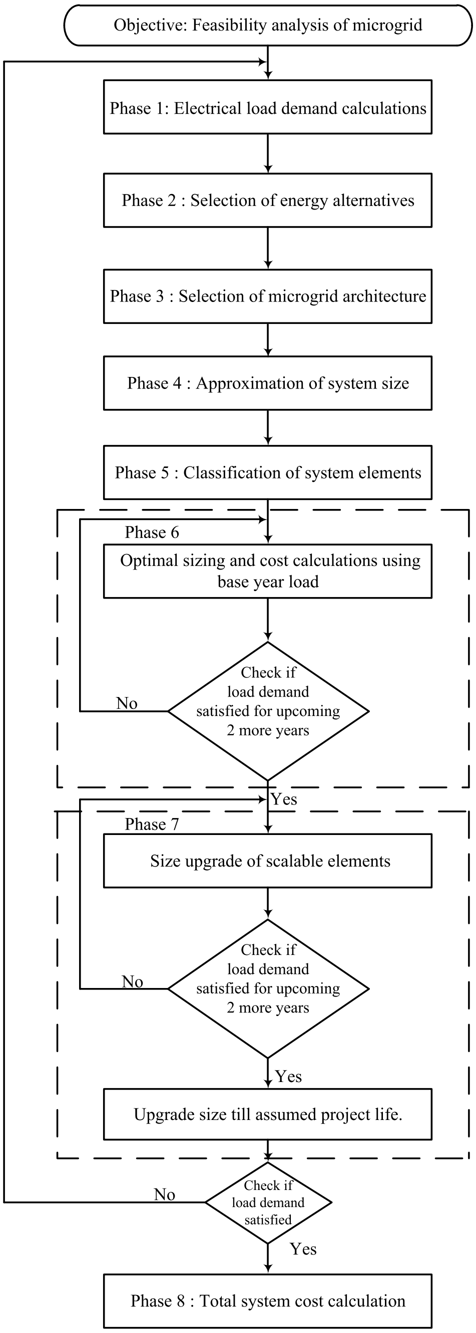


FIGURE 3. **Proposed multiyear approach for techno-financial analysis of energy systems.**

Phase 5 (Classification of System Elements): Classify the different elements of energy system such as RETs, conventional generators (diesel generator), converters and storage technologies, into fixed and scalable type. Fixed type elements are those whose size and capacity has to be kept same over the project lifetime such as photovoltaics (PV), converters, etc. and scalable are those depending upon the increase in load demand can be upgraded such as small wind turbines, batteries, diesel generators, etc.

Phase 6 (Optimal Sizing and Cost Calculations Using Base Year Load): Using any of the optimization methods or models or software tool described above [112]–[114], [118]–[123], calculate the optimal sizing of the energy system using the total connected load of the initial or base year (1st year). This optimal energy system should be able to satisfy the current load demand as well as the demand of at least upcoming two more years. All the costings such as net present cost (NPC), capital cost (CC), operation and maintenance cost ($O\ \&\ M$) and cost of electricity (COE) should be calculated for each year. During the next two years (excluding the initial year), the system will not be upgraded so the capital cost should be zero. However, the NPC, $O\ \&\ M$ cost and COE should be calculated on a yearly basis.

Phase 7 (Size Upgrade of Scalable Elements): Upgrade the size of scalable elements for the 4th year in such a way that system should be able to satisfy the load demand of the 4^{th} year and coming next two years. Calculate the cost as mentioned in phase 6. The system size is upgraded in a step size of 2 years only excluding the year in which the system size is being upgraded. Whenever the system will be upgraded it should be able to meet the demand of the year in which the upgrade is done and for upcoming two more years. For example, if the system is designed using load data of the year 2015 (base year), it should be able to satisfy the increasing load demand minimum till 2017 (step size is two years excluding the base year). The system should be upgraded in the year 2018 (4th year) in such a manner that it should be able to satisfy the growing load demand of the year 2018 and for a minimum of two more coming years (till 2020) and so on.

Phase 8 (Total System Cost Calculations): Final costing of the energy system is calculated using the following equations:

If x_n = total project lifetime in years,

$x_n = 1$ = initial or base year. Then,

Total capital cost (CC_{total}) of the system,

$$CC_{total} = \sum_{x_n=1}^{x_n} CC_{x_n} \tag{2}$$

Total net present cost (NPC_{total}) of the system,

$$NPC_{total} = \sum_{x_n=1}^{x_n} NPC_{x_n} \tag{3}$$

Total operation & maintenance cost ($O\ \&\ M_{total}$) of system,

$$O\ \&\ M_{total} = \sum_{x_n=1}^{x_n} (O\&M)_{x_n} \tag{4}$$

Total cost of electricity (COE_{total})

$$COE_{total} = \frac{1}{x_n} \sum_{x_n=1}^{x_n} (COE)_{x_n} \tag{5}$$

D. STAGE-4: APPLICATION OF DECISION ANALYSIS TOOLS FOR FINAL PROJECT SELECTION (FIGURE 1 AT STAGE -4)

Once the detailed techno-financial analysis of the energy system considering different architectures is completed, then decision analysis tool should be utilized to determine the optimal robust, reliable and cost-effective system. Depending on the available data obtained from techno-economic analysis and expert views, the appropriate methods as well criteria should be used for the analysis. There are several MCDM models available which can be broadly classified into value measurement, goal reference model, utility-based model and outranking models [28]. The authors in [28], [88]–[90], and [132] have presented a detailed analysis of various MCDM models utilized in renewable energy planning with a way for their selection. However, all of them agreed that no MCDM model or techniques could be ranked best or worst as every MCDM models have their own strength and weakness as explained by various scholars [28], [43], [88]–[91], [132], [133]. The selection of appropriate decision analysis method is made mostly by the objective of the problem, the availability of data, the key performance indices for evaluation, practical consideration in view of the problem etc. and sometimes with expert advice [28], [88]–[90], [132]. Usually, the data obtained after techno-financial analysis are quantities with incommensurate units. For such type of problems hybrid MCDM models such as Technique for Order Preference by Similarity to Ideal Solutions (TOPSIS) method in conjunction with other MCDM methods such as analytical hierarchy process (AHP), sum weighted method (SWM), additive ratio assessment (ARAS), fuzzy logic, etc. can be applied for final energy project selection. Rich literature is available on the usages of such integrated models in energy planning [79], [80], [85]–[87], [134]–[144]. The comprehensive framework described in previous section II is utilized to design a rural microgrid for a remote village in the Himalayas in the following section.

III. CASE STUDY: IMPLEMENTATION OF THE FRAMEWORK

The village taken up for the case study is located in North-Eastern region of India. The village, Leporiang is a small Tehsil in Papum Pare, India located at 27.12° N 93.2° E with an average elevation of 1089 M [110], [111]. A primary technical and financial study of the village has been reported by the authors in [110] and [111]. In [110], a detailed survey for preliminary analysis of the Leporiang village was carried out to generate an approximate load and energy demand profile based on the data collected in February 2014. Also, a hybrid microgrid based on the combination of solar photovoltaic (PV), wind turbine (WT), hydro, diesel generator (DG) and battery to electrify the village was also illustrated. However, the study [110] only concentrated towards the technical evaluation of the microgrid design and no analysis was presented based on social, environmental and economic factors. Feasibility analysis of the microgrid based on PV, WT, DG, and battery using a linear optimization method for minimizing the cost by using various sizes of battery storage using only the domestic load of the village was outlined in [111]. In this present case study, the detailed framework as illustrated in detail in section II will be utilized to design the microgrid considering technical, economic, social and environmental aspects which are being presented in the following sub-sections.

TABLE 1. Data of Leporiang village.

Data Type	February 2014 [110, 111]			August 2015 [43]		
Number of houses	250			250		
Population	1500			1500		
Average Income/Family	INR 100000			INR 225000-350000		
Load Type (kW)	*Base (kW)*	*Peak (kW)*	*Total Connected Load (kW)*	*Base (kW)*	*Peak (kW)*	*Total Connected Load (kW)*
Domestic	30	72	83	38	101	110
Office	2.24	10.28	12	3.16	13.8	14.54
School	2.15	8.5	9.6	2.8	10.6	12
Summary	Total Load (kW)		104.6	Total Load (kW)		136.54
	Total Energy demand (kWh/day)		693.41	Total Energy demand (kWh/day)		876.41

A. DATA COLLECTION FROM TARGET SITE (SEC. II.A STAGE-1 DESIGN)

Individual interviews and interactions were carried out with a particular set of questions to understand the electrical demand as well as the socio-economic and environmental characteristics of the community [43], [110], [111]. Many group meetings and workshops with the village elders/decision making leaders along with the community inhabitants were carried out regularly to educate and motivate them positively with the welfare of the villagers upon successful completion of the project [43], [110]. Details of the electrical load demand, income, population, etc. generated from the data collected after the surveys is shown in Table 1. The recent development of National Highways giving much better road connectivity to the nearest town and markets has helped the overall economic development of the village [43]. Due to the rise in income, the local people have bought many new electrical appliances specifically television, refrigerator and water heater, etc. which has led to the abrupt increase in the electrical load demand in a period of just 18 months particularly in domestic load profile as illustrated Table 1.

B. SELECTION OF PERFORMANCE INDICATORS/CRITERIA AND ENERGY ALTERNATIVES (SEC. II.A STAGE-1 DESIGN)

The data collected in Table 1 is presented to the experts from industry, academics, government organization, and non-government organizations working in the field of rural electrification projects for their counsel to categorize the alternatives and the criterion for evaluation [43]. Identification of criteria for evaluation is essential and needs a very composed approach. As observed from Table 1, the load demand suddenly increased in a period of 18 months only, so the experts advised to include scalability as one of the criteria for evaluation of the alternatives. So, the alternative and criteria selection must be made in a clear-cut way keeping the interest of all the actors involved in the project [28], [43], [81]–[87]. The selection of alternatives and criteria as deliberated in Table 2 and Table 3 is based on the process as illustrated in stage −1, Figure 2 of sub-section II.A. 12 alternatives to be evaluated on 4 criteria and 18 sub-criteria's were taken as shown in Tables 2 and 3 respectively as detailed by Kumar *et al.* [43].

TABLE 2. List of energy alternatives used in microgrid design (source: author [43] with permission from the publisher).

SN	Energy sources	Storage	Configuration
1.	Photovoltaics (PV)	Battery	Centralized Off Grid
2.	Wind	Battery	Centralized Off Grid
3.	PV, Wind (PVW)	Battery	Centralized Off Grid
4.	PV, Diesel Generator (PVDG)	Battery	Centralized Off Grid
5.	Wind, Diesel Generator (WDG)	Battery	Centralized Off Grid
6.	PV, Wind, Diesel Generator (PVWDG)	Battery	Centralized Off Grid
7.	PV	Battery	Centralized Grid
8.	Wind	Battery	Centralized Grid
9.	PV, Wind (PVW)	Battery	Centralized Grid
10.	PV, Diesel Generator (PVDG)	Battery	Centralized Grid
11.	Wind , Diesel Generator (WDG)	Battery	Centralized Grid
12.	PV, Wind, Diesel Generator (PVWDG)	Battery	Centralized Grid

TABLE 3. Details of criteria/sub-criteria utilized for sustainable evaluation of energy alternatives (source: author [43] with permission from the publisher).

SN	Criteria	Sub-Criteria	
1.	Technical	I.	Efficiency (EFF)
		II.	Meeting the load demand (LD)
		III.	Power Quality (PQ)
		IV.	Reliability (RE)
		V.	Life Span (LS)
		VI.	Scalability (SI)
		VII.	Technical Maturity (TM)
2.	Social	VIII.	Public Acceptance (PA)
		IX.	Human Development Index (HDI)
		X.	Health Issues (HI)
		XI.	Creation of Jobs
3.	Economic	XII.	Capital cost (CC)
		XIII.	Installation cost (IC)
		XIV.	Operation & Maintenance cost (O & M)
		XV.	Fuel Cost (FC)
4.	Environmental	XVI.	Particle Emission (PE)
		XVII.	Noise
		XVIII.	Land used (LU)

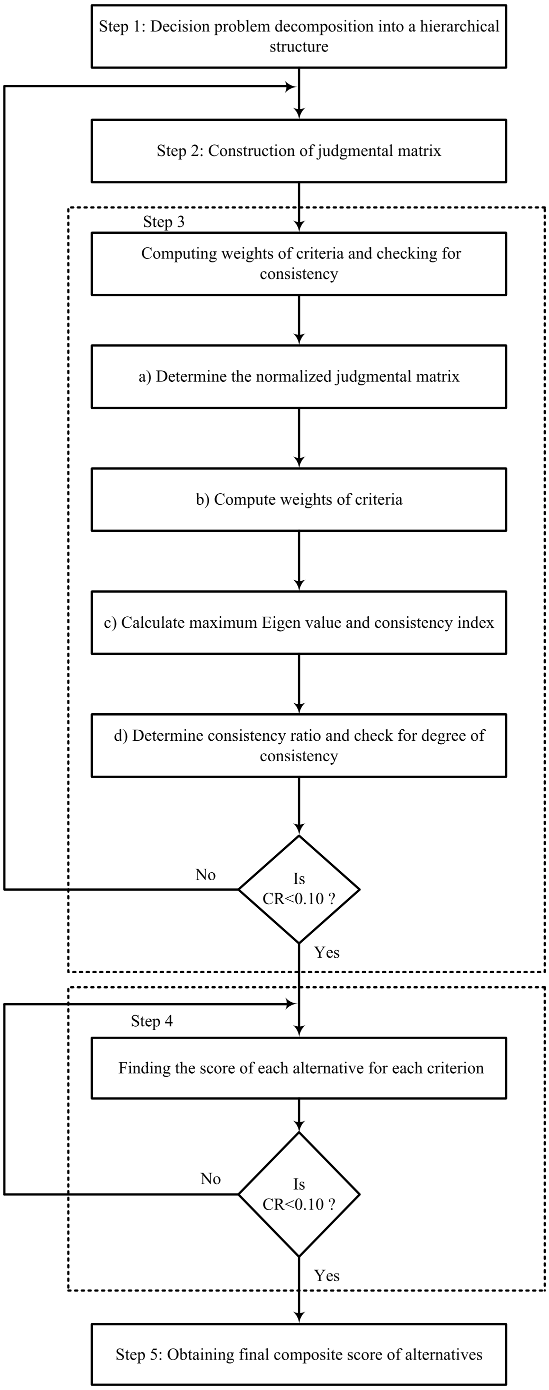


FIGURE 4. Flowchart for implementation of AHP based on methodology outlined in [145]–[155].

C. APPLICATION OF MCDA TOOLS FOR EVALUATION (SEC. II.A STAGE-1 DESIGN)

AHP tool is adapted for the selection of suitable alternatives. AHP can handle quantifiable and subjective criteria, and its approach is very simple, flexible and efficient [90]. It also allows one to check the consistency of the decision taken. AHP was proposed by Saaty and Vargas [145]. The details regarding the implementation of AHP method is illustrated with the help of a flowchart shown in Figure 4 and its detailed explanation to find criteria weights and rank the alternatives is described below [145]–[155]:

Step 1 (Decision Problem Decomposition Into a Hierarchical Structure):

- Structure the decision problem in to a hierarchical model as illustrated in Figure 5.
- As illustrated in Fig. the problem can be decomposed in to different levels comprising of main objective (goal), criteria/sub-criteria and alternatives.

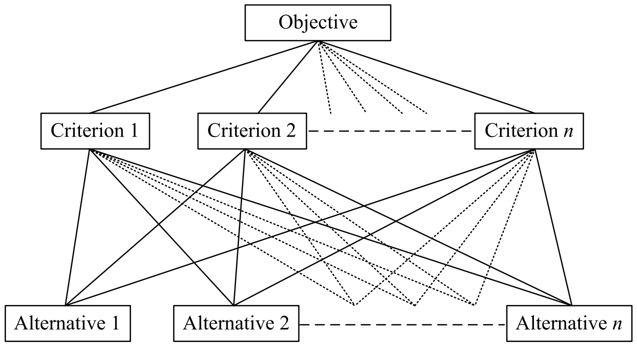


FIGURE 5. Basic hierarchical structure of AHP [145].

TABLE 4. Saaty's fundamental scale [145].

a_{gh} Scale / values	Explanation of the values
1	Both g and h objectives are equally important.
3	*g* is moderately important than *h*.
5	*g* is strongly important in comparison to *h*.
7	*g* is dominantly strongly over objective *h*.
9	*g* is assigned undeniably most importance to objective h.
2, 4, 6, 8	Intermediary scale, for example, a scale of 4 means that *g* is midway between moderately and strongly more important than *h*.

Step 2 (Construction of Judgmental Matrix):

- A judgmental matrix (*Aj*) by performing pairwise comparison, is framed based on available quantitative or qualitative data. Application of verbal judgments of the decision-maker is mainly utilized for qualitative data based on a pre-defined scale as shown in Table 4 given by Saaty.
- The pairwise comparison has to be performed between the element in row *g*and column *h* of *Aj* (called a_{gh}) which specifies how much more important or strong *g* is than *h* based on speciafied criteria/alternatives.

Rules for constructing the judgmental matrix using pairwise comparison:

1. If n = total number of criteria/sub-criteria defined, then a judgmental matrix (Aj) of $n \times n$ has to be formed.
2. If $a_{gh} = \alpha$, then $a_{hg} = 1/\alpha$ where, α = the constant value (1-9, from Table 4).
3. If g is found to be of equal importance as *h*, then $a_{gh} = a_{hg} = 1$ and $a_{gg} = 1$ for all *g*.

TABLE 5. **Different values of random index (RI_n).**

n	1	2	3	4	5	6	7	8	9	10	11	12	13	14
RI_n	0	0	0.58	0.90	1.12	1.24	1.32	1.41	1.45	1.49	1.51	1.48	1.56	1.57

Judgmental matrix of n criteria,

$$A_{j(n\times n)} = \begin{bmatrix} a_{g_1h_1} & a_{g_1h_2} & a_{g_1h_3} & \cdots\cdots\cdots & a_{g_1h_n} \\ a_{g_2h_1} & a_{g_2h_2} & a_{g_2h_3} & \cdots\cdots\cdots & a_{g_2h_n} \\ a_{g_3h_1} & a_{g_3h_2} & a_{g_3h_2} & \cdots\cdots\cdots & a_{g_3h_n} \\ a_{g_nh_1} & a_{g_nh_2} & a_{g_nh_3} & \cdots\cdots\cdots & a_{g_nh_n} \end{bmatrix} \tag{6}$$

Step 3 (Computing Weights of Criteria and Checking for Consistency):

1) DETERMINE THE NORMALIZED JUDGMENTAL MATRIX

In order to find the normalized matrix (A_{nrmlz}), divide all the columns individually of A_j by their entry in the respective values in h column by all total sum of all the values in column a particular column h.

From eq. (6), sum of the elements of column $h_1, h_2, h_3 \ldots\ldots.h_n$ can be given as,

$$S_{1(sum)} = (a_{g_1h_1} + a_{g_2h_1} + a_{g_3h_1} + \ldots\ldots. + a_{g_nh_1}) \tag{7}$$

$$S_{2(sum)} = (a_{g_1h_2} + a_{g_2h_2} + a_{g_3h_2} + \ldots\ldots. + a_{g_nh_2}) \tag{8}$$

$$S_{3(sum)} = (a_{g_1h_3} + a_{g_2h_3} + a_{g_3h_3} + \ldots\ldots. + a_{g_nh_3}) \tag{9}$$

$$\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots$$

$$S_{n(sum)} = (a_{g_1h_n} + a_{g_2h_n} + a_{g_3h_n} + \ldots\ldots. + a_{g_nh_n}) \tag{10}$$

So, the nomalized matrix can be dervied as (11), as shown at the bottom of this page. The sum of all the entries in each of the coulumn of normalized matrix A_{nrmlz} is always unity.

2) COMPUTE WEIGHTS OF CRITERIA

To determine the weights (W_s) from A_j, which indicates the weight that each criteria is given in the pairwise comparison matrix, the average of the entries in row i of A_{nrmlz}, [see (12), as shown at the bottom of this page].

3) CALCULATE MAXIMUM EIGEN VALUE ($\lambda_{\max}$) AND CONSISTENCY INDEX (CI)

Once the criteria weights are determined, calculate the maximum eigenvalue ($\lambda_{\max}$)using following equation,

$$\lambda_{\max} = \frac{1}{n}\sum_{g=1}^{n} \frac{g^{th} entry A_j (W_s)^T}{g^{th} entry (W_s)^T} \tag{13}$$

where,

A_j = initial judgmental matrix

$(W_s)^T$ = Transpose of criteria weights

Using the calculated λ_{max} values to find out the consistency index for n number of criteria (CI_n) as follows,

$$CI_n = \frac{(\lambda_{max}) - n}{n-1} \tag{14}$$

Lower calculated value of CI_n signifies minimal deviations from the consistency in making the pairwise comparison by decision makers and the determined weights are useful enough with respect to the primary objective.

4) DETERMINE CONSISTENCY RATIO (CR) AND CHECK FOR DEGREE OF CONSISTENCY

Consistency ratio is calculated by taking a ratio between CI_n to the random index (RI_n). The RI_n is a constant which has an individual values based on the value of n as shown in Table 5 below.

$$CR = \left(\frac{CI_n}{RI_n}\right) \tag{15}$$

- Alonso and Lamata [156] has deliberated different values of the random index (RI_n) for calculation of consistency ratio (CR) when the value of n (criteria) is more than 15 due to which more number of criteria can be accommodated for evaluation using AHP method in the same framework.
- The degree of consistency is only acceptable if the value of $CR < 0.10$. However, if the $CR > 0.10$, then very

$$A_{nrmlz} = \begin{bmatrix} a_{g_1h_1}/S_{1(sum)} & a_{g_1h_2}/S_{2(sum)} & a_{g_1h_3}/S_{3(sum)} & \cdots\cdots\cdots & a_{g_1h_n}/S_{n(sum)} \\ a_{g_2h_1}/S_{1(sum)} & a_{g_2h_2}/S_{2(sum)} & a_{g_2h_3}/S_{3(sum)} & \cdots\cdots\cdots & a_{g_2h_n}/S_{n(sum)} \\ a_{g_3h_1}/S_{1(sum)} & a_{g_3h_2}/S_{2(sum)} & a_{g_3h_2}/S_{3(sum)} & \cdots\cdots\cdots & a_{g_3h_n}/S_{n(sum)} \\ a_{g_nh_1}/S_{1(sum)} & a_{g_nh_2}/S_{2(sum)} & a_{g_nh_3}/S_{3(sum)} & \cdots\cdots\cdots & a_{g_nh_n}/S_{n(sum)} \end{bmatrix} \tag{11}$$

$$W_s = \frac{1}{n}\begin{bmatrix} a_{g_1h_1}/S_{1(sum)} & a_{g_1h_2}/S_{2(sum)} & a_{g_1h_3}/S_{3(sum)} & \cdots\cdots\cdots & a_{g_1h_n}/S_{n(sum)} \\ a_{g_2h_1}/S_{1(sum)} & a_{g_2h_2}/S_{2(sum)} & a_{g_2h_3}/S_{3(sum)} & \cdots\cdots\cdots & a_{g_2h_n}/S_{n(sum)} \\ a_{g_3h_1}/S_{1(sum)} & a_{g_3h_2}/S_{2(sum)} & a_{g_3h_2}/S_{3(sum)} & \cdots\cdots\cdots & a_{g_3h_n}/S_{n(sum)} \\ a_{g_nh_1}/S_{1(sum)} & a_{g_nh_2}/S_{2(sum)} & a_{g_nh_3}/S_{3(sum)} & \cdots\cdots\cdots & a_{g_nh_n}/S_{n(sum)} \end{bmatrix} = \begin{bmatrix} w_{s_1} \\ w_{s_2} \\ w_{s_3} \\ \cdots\cdots \\ w_{s_n} \end{bmatrix} \tag{12}$$

serious discrepancies exists and the AHP does not yield any significant results.

- So, at any instance if the inconsistent solutions are obtained while calculating the weightage based on AHP then steps from 1 to 3 should be repeated until the degree of consistency is satisfactory.

Step 4 (Finding the Score of Each Alternative for Each Criterion):

- If, m = total number of alternatives, then the alternative judgmental matrix (Al_{jdm}) of $m \times m$ has to be formed following similar procedure as specified in step 2 to formulate the alterative matrix on each defined criteria/ sub-criteria.
- For example, if the number of defined criteria is 5 then all the alternatives have to be evaluated on 5 defined criteria. In other words, depending upon the number of criteria's that many number of alternative matrix has to be formed.
- Following the step 3, determine the initial priority or relative weight score of alternatives (W_m) on each defined criteria maintaining the degree of consistency.

$$W_m = \left[\, W_{m(n_1)} \; W_{m(n_2)} \; W_{m(n_3)} \ldots\ldots\ldots \; W_{m(n_n)} \,\right] \quad (16)$$

where, $W_{m(n_1)}, W_{m(n_2)}, W_{m(n_3)}, \ldots\ldots W_{m(n_n)}$ = calculated initial priority or weight score of alternatives on criteria's $n_1, n_2, n_3 \ldots\ldots n_n.$

Formulate a final alternative weight matrix ($FW_{m\times n}$) of dimension $m \times n$ *(alternative* $\times$ *criteria)* as follows,

$$FW_{(m\times n)} = \begin{bmatrix} w_{m_1n_1} & w_{m_1n_2} & w_{m_1n_3} & \cdots\cdots & w_{m_1n_n} \\ w_{m_2n_1} & w_{m_2n_2} & w_{m_2n_3} & \cdots\cdots & w_{m_2n_n} \\ w_{m_3n_1} & w_{m_3n_2} & w_{m_3n_3} & \cdots\cdots & w_{m_3n_n} \\ \cdots\cdots & \cdots\cdots & \cdots\cdots & \cdots\cdots & \cdots\cdots \\ w_{m_mn_1} & w_{m_mn_2} & w_{m_mn_3} & \cdots\cdots & w_{m_mn_n} \end{bmatrix} \quad (17)$$

Step 5 (Obtaining Final Composite Score of Alternatives): In order to obtain the final composite score (FCS_m) of the alternatives based on the defined criteria to obtain the overall result considering the main objective or goal, following equation is used

$$FCS_m = [FW_{m\times n}]\,[W_s] = \begin{bmatrix} w_{m_1n_1} & w_{m_1n_2} & w_{m_1n_3} & \cdots\cdots & w_{m_1n_n} \\ w_{m_2n_1} & w_{m_2n_2} & w_{m_2n_3} & \cdots\cdots & w_{m_2n_n} \\ w_{m_3n_1} & w_{m_3n_2} & w_{m_3n_3} & \cdots\cdots & w_{m_3n_n} \\ \cdots\cdots & \cdots\cdots & \cdots\cdots & \cdots\cdots & \cdots\cdots \\ w_{m_mn_1} & w_{m_mn_2} & w_{m_mn_3} & \cdots\cdots & w_{m_mn_n} \end{bmatrix} \times \begin{bmatrix} w_{s_1} \\ w_{s_2} \\ w_{s_3} \\ \cdots\cdots \\ w_{s_n} \end{bmatrix} = \begin{bmatrix} FCS_{m_1} \\ FCS_{m_2} \\ FCS_{m_3} \\ \cdots\cdots \\ FCS_{m_m} \end{bmatrix} \quad (18)$$

Where, $FCS_{m_1}, FCS_{m_2}, FCS_{m_3}, \ldots\ldots FCS_{m_m}$ = final composite score of alternatives m_1,m_2, m_3, m_m. Now the final ranking of the alternatives should be based on the obtained FCS_m. The alternative with the overall highest score should be ranked first, the second highest second rank and so on.

Due to the development of new programming tools such as MATLAB, it has become much easier and possible to accommodate more number of criteria in AHP framework in a very efficient and easy manner as compared to the manual determination of criteria weights. In order to get a more realistic solution author in [28] has specifically pointed out to carry out the evaluation of alternatives in preliminary selection based on multiple scenarios by prioritizing the criteria's. In this study depending upon the expert advice four scenarios were considered by prioritizing different criteria as follows:

1st Scenario-Environmental > Social > Technical > Economic

2nd Scenario-Technical > Social > Economic > Environmental [43].

3rd Scenario-Social > Technical > Economic > Environmental [43].

4th Scenario-Economic > Social > Technical > Environmental

In the first scenario as specified above the environmental criteria has the utmost priority followed by social, technical and economic criteria. The preliminary judgmental matrix for the criteria's is acquired using Satty scale [145] and their criteria weights (W_s) are obtained following the method illustrated in Figure 4 [28], [43], [145]–[155]. Table 6 shows the criteria weights (W_s) obtained in view of 1st scenario. In the first scenario, the sum of the criteria weights (W_s) of the environmental criteria (namely PE, noise and LU) is 0.5644 which is highest followed by social (0.1749), technical (0.1462) and economic (0.1125) criteria's which is also shown in Figure 6.

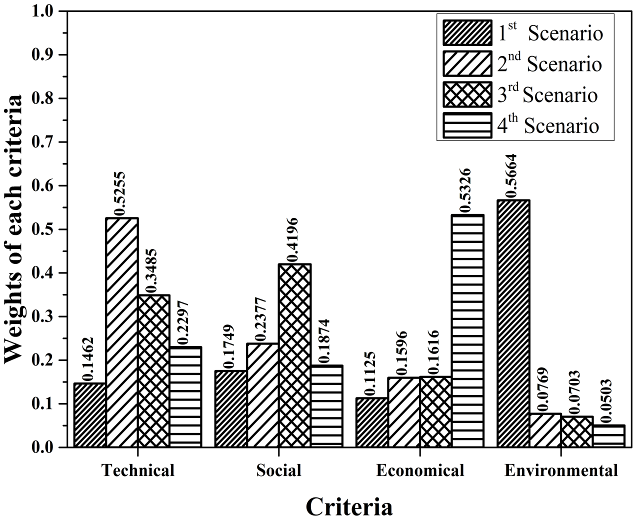


FIGURE 6. Weights of criteria on different scenarios.

Similarly, for the other three scenarios the criteria weights (W_s) are determined, and their judgmental matrix along with W_s are illustrated in the *supplementary material (Section A, Table A.1-A.3).* Figure 6 illustrates the

TABLE 6. Criteria comparison matrix (Criteria X Criteria).

	PA	HDI	HI	Job	EFF	LD	PQ	RE	LS	SI	TM	CC	IC	O & M	FC	PE	Noise	LU	W_s
PA	1.00	1.00	1.00	1.00	4.00	3.00	5.00	4.00	4.00	4.00	4.00	0.50	1.00	1.00	1.00	0.14	0.14	0.11	0.0465
HDI	1.00	1.00	1.00	1.00	4.00	5.00	3.00	3.00	3.00	3.00	3.00	0.50	1.00	1.00	1.00	0.14	0.14	0.11	0.0427
HI	1.00	1.00	1.00	1.00	4.00	4.00	3.00	4.00	4.00	5.00	5.00	0.50	1.00	1.00	1.00	0.14	0.14	0.11	0.0475
Jobs	1.00	1.00	1.00	1.00	1.00	2.00	2.00	3.00	4.00	4.00	5.00	0.50	1.00	1.00	1.00	0.14	0.14	0.11	0.0382
EFF	0.25	0.25	0.25	1.00	1.00	1.00	2.00	3.00	3.00	3.00	3.00	0.50	1.00	1.00	1.00	0.14	0.14	0.11	0.0293
LD	0.33	0.20	0.25	0.50	1.00	1.00	3.00	3.00	3.00	3.00	3.00	0.50	1.00	1.00	1.00	0.14	0.14	0.11	0.0296
PQ	0.20	0.33	0.33	0.50	0.50	0.33	1.00	1.00	1.00	1.00	1.00	0.50	1.00	1.00	1.00	0.14	0.14	0.11	0.018
RE	0.25	0.33	0.25	0.33	0.33	0.33	1.00	1.00	1.00	1.00	1.00	0.50	1.00	1.00	1.00	0.14	0.14	0.11	0.0175
LS	0.25	0.33	0.25	0.25	0.33	0.33	1.00	1.00	1.00	1.00	1.00	0.50	1.00	1.00	1.00	0.14	0.14	0.11	0.0173
SI	0.25	0.33	0.20	0.25	0.33	0.33	1.00	1.00	1.00	1.00	1.00	0.50	1.00	1.00	1.00	0.14	0.14	0.11	0.0173
TM	0.25	0.33	0.20	0.20	0.33	0.33	1.00	1.00	1.00	1.00	1.00	0.50	1.00	1.00	1.00	0.14	0.14	0.11	0.0172
CC	2.00	2.00	2.00	2.00	2.00	2.00	2.00	2.00	2.00	2.00	2.00	1.00	1.00	1.00	1.00	0.14	0.14	0.11	0.0387
IC	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	0.14	0.14	0.11	0.0246
O & M	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	0.14	0.14	0.11	0.0246
FC	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	0.14	0.14	0.11	0.0246
PE	7.00	7.00	7.00	7.00	7.00	7.00	7.00	7.00	7.00	7.00	7.00	7.00	7.00	7.00	7.00	1.00	1.00	1.00	0.1753
Noise	7.00	7.00	7.00	7.00	7.00	7.00	7.00	7.00	7.00	7.00	7.00	7.00	7.00	7.00	7.00	1.00	1.00	1.00	0.1753
LU	9.00	9.00	9.00	9.00	9.00	9.00	9.00	9.00	9.00	9.00	9.00	9.00	9.00	9.00	9.00	1.00	1.00	1.00	0.2158
Consistency Ratio (CR) = 0.0474																			

TABLE 7. Alternative comparison matrix (alternative X alternative) evaluated on public acceptance.

Configuration / Alternative		Isolated						Grid						W_m
		PV	Wind	PVW	PVDG	WDG	PVWDG	PV	Wind	PVW	PVDG	WDG	PVWDG	
Isolated	PV	1	1	1	3	3	5	2	3	5	5	5	7	0.1734
	Wind	1	1	1	2	2	5	2	2	5	5	5	7	0.1554
	PVW	1	1	1	2	2	5	2	2	5	5	5	7	0.1554
	PVDG	0.3333	0.5	0.5	1	1	5	1	3	3	3	3	7	0.1004
	WDG	0.3333	0.5	0.5	1	1	3	1	3	3	3	3	3	0.0874
	PVWDG	0.2	0.2	0.2	0.2	0.3333	1	3	3	3	3	3	3	0.0724
Grid	PV	0.5	0.5	0.5	1	1	0.3333	1	3	3	3	3	3	0.0814
	Wind	0.3333	0.5	0.5	0.3333	0.3333	0.3333	0.3333	1	3	3	3	3	0.0575
	PVW	0.2	0.2	0.2	0.3333	0.3333	0.3333	0.3333	0.3333	1	3	3	3	0.0393
	PVDG	0.2	0.2	0.2	0.3333	0.3333	0.3333	0.3333	0.3333	0.3333	1	3	3	0.0327
	WDG	0.2	0.2	0.2	0.3333	0.3333	0.3333	0.3333	0.3333	0.3333	0.3333	1	3	0.0267
	PVWDG	0.1429	0.1429	0.1429	0.1429	0.3333	0.3333	0.3333	0.3333	0.3333	0.3333	0.3333	1	0.018
Consistency Ratio (CR) = 0.079														

sum of relative weights of criteria (W_s) with different scenarios. Following the process as illustrated in Figure 4 [28] [43], [145]–[155], the alternatives will be evaluated based on the total of 20 criteria's as outlined in Table 3. Table 7 illustrates the preliminary alternative judgmental matrix along with its relative weight (W_m) when evaluated on one of the social criteria namely public acceptance (PA).

A total of 20 alternative judgmental matrices is constructed, and the relative weights of alternatives on each criteria's are determined. Finally a relative weight matrix ($FW_{m\times n}$) of alternatives x criteria in this case a 12 x 20 RWM is obtained. The final scores are then calculated for the alternatives by multiplying the alternative relative weight matrix ($FW_{m\times n}$) by the criteria weights (W_s) for different scenarios. As each scenario has different criteria weights, the final scores obtained will be different for the alternatives in different scenarios. The final ranking is then done solely on the scores obtained. The alternatives with the highest score is ranked first and so on. Table 8 shows the final results of the alternatives based on all the scenario.

As illustrated in Table 8, PVWDG has the highest score in all the scenarios in isolated mode followed by PVW. In grid-connected mode, also PVWDG and PVW are the best two in all scenarios followed by WDG and PVDG. When overall ranking is seen, PVWDG (grid connected) has the top rank followed by PVW (grid connected) and PVWDG (isolated) in all the scenarios. Even though the rankings of the alternatives seems to be same in all the scenarios but the final score varies. Final results from the preliminary selection of the alternatives are thus obtained which are presented to the experts and stakeholder for their views, and then further analysis is carried out.

TABLE 8. Rankings of the alternatives on various scenarios.

Configuration	Alternatives	Final Scores on different scenarios				Rankings with various scenarios											
						1st			2nd			3rd			4th		
		1st	2nd	3rd	4th	Isolated	Grid	Overall	Isolated	Grid	Overall	Isolated	Grid	Overall	Isolated	Grid	Overall
Isolated	PV	0.006	0.0083	0.0077	0.007	2nd		8th	5th		9th	6th		12th	4th		8th
	Wind	0.0059	0.0084	0.0080	0.0078	3rd		9th	4th		10th	5th		11th	2nd		6th
	PVW	**0.0059**	**0.0113**	**0.0096**	**0.0076**	**3rd**		**10th**	**2nd**		**7th**	**2nd**		**8th**	**3rd**		**7th**
	PVDG	0.0047	0.0107	0.0088	0.0061	5th		11h	3rd		8th	4th		10th	6th		12th
	WDG	0.0052	0.0107	0.0092	0.0065	4th		12th	3rd		8th	3rd		9th	5th		11th
	PVWDG	**0.0097**	**0.0279**	**0.0213**	**0.0121**	**1st**		**3rd**	**1st**		**3rd**	**1st**		**3rd**	**1st**		**3rd**
Grid	PV	0.0063	0.012	0.0098	0.007		6th	7th		6th	6th		5th	6th		5th	9th
	Wind	0.0064	0.0119	0.0097	0.007		5th	6th		5th	6th		6th	7th		5th	10th
	PVW	**0.0102**	**0.0283**	**0.0216**	**0.0131**		**2nd**	**2nd**		**2nd**	**2nd**		**2nd**	**2nd**		**2nd**	**2nd**
	PVDG	**0.0081**	**0.025**	**0.0188**	**0.0107**		**4th**	**5th**		**4th**	**5th**		**4th**	**5th**		**3rd**	**5th**
	WDG	**0.0089**	**0.0253**	**0.0191**	**0.011**		**3rd**	**4th**		**3rd**	**4th**		**3rd**	**4th**		**4th**	**4th**
	PVWDG	**0.0212**	**0.0688**	**0.0509**	**0.0279**		**1st**	**1st**		**1st**	**1st**		**1st**	**1st**		**1st**	**1st**

D. LOAD GROWTH PROJECTIONS (SEC.II.B, STAGE-2 DESIGN)

As explained in sub-sections II.B and III.A, the growing economic condition and infrastructural development are some of the causes to raise the electrical load, in particular for the rural location. Even at such disintegrated levels, the growth in gross domestic product (GDP) rate has direct effects on the overall development of the region and thus leading to rise in the energy demand [1], [9], [11], [28], [157], [158]. According to World Bank [157], India's GDP rate in 2015 was 7.6 % and is expected to rise to 7.9 % by 2018. So, considering all the facts and with prior discussion with possible project investors and technical experts, a growth rate of 7.9 % is used for projecting the load demand using equation (1).

E. TECHNO-FINANCIAL ANALYSIS (SEC.II.C, STAGE-3 DESIGN)

Out of 12 energy alternatives, a total of best six choices (two from isolated and four from grid connected mode) are selected for techno-financial analysis. Alternatives highlighted in bold in Table 8 are taken up for the investigation with different microgrid architectures.

1) SYSTEM COMPONENTS PARAMETERS FOR SIMULATION

As already mentioned in the previous sub-section (III.C) the power system contains following elements along with various key parameters used for analysis whose specific details are as follows:

i) Photovoltaic (PV): 1 kW fixed type solar panel with a capital cost of Indian National Rupee (INR) 53000/kW with an operation & maintenance cost (O & M) of INR 700/year is chosen. The capital cost includes the cost of, "the module, civil and general works, mounting structures, power conditioning unit, land, evacuation, preliminary and pre-operative expenses" as recommended by central electricity regulatory commission (CERC), Government of India [159]. The general output electrical power (P_{PVT}) generated by the PV array system can be calculated using following equations [161]:

$$P_{PVT} = R_{cpv} f_{pv} \left[\frac{G_{PVM}}{G_{STC}} \right] \left[1 + \alpha_p (T_{PVM} - T_{STC}) \right] \quad (19)$$

Where, R_{cpv} is the rated power output of the PV array module under standard testing condition (STC) in kW. f_{pv} is derating factor of the PV (%). G_{PVM} is amount of solar isolation incident of the module in current time step (kW/m^2). G_{STC} is the incident radiation at STC (kW/m^2). α_p is module temperature coefficient of power (%/°C). T_{PVM} is PV call ambient temperature (°C). T_{STC} is PV cell temperature at STC (°C).

ii) Wind Turbine (WT): A 10 kW wind turbine with a capital cost of INR 619800 and an O & M cost of INR 11240/10kW is taken [154], [155]. The details regarding wind turbine characteristics can be found at [161]–[163]. The power generated (P_{WT}) from wind turbine is given as

$$P_{WT} = \frac{1}{2} \rho A v^3 C_p \quad (20)$$

Where, ρ is air density (kg/m^3). A is area swept by the wind turbine blades. v is the wind velocity (m/s) at hub height. C_p is power coefficient. The power curve of wind turbine is based on manufacture datasheet [162], [163] is shown in Figure 7.

iii) Diesel Generator (DG): A 1 kW DG with a capital cost of INR 15000 and O & M cost of INR 15/hr is taken up for the

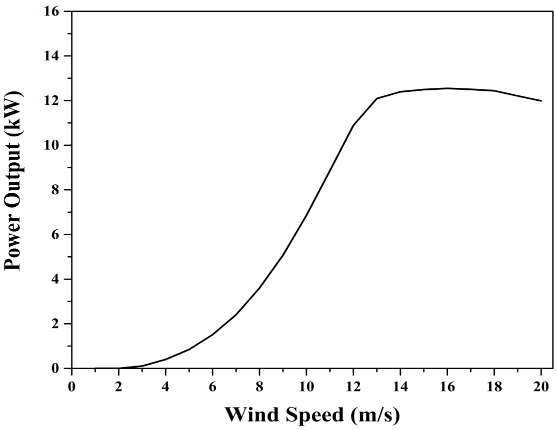


FIGURE 7. Wind turbine power curve [162], [163].

analysis [49], [160], [164]. The diesel generator total average efficiency in terms of generated electrical energy and heat for a year is given as [161]:

$$\eta_{gen} = \frac{3.6(E_{gen} + H_{gen})}{m_{fuel} LHV_{fuel}} \tag{21}$$

Where, m_{fuel} is generator total annual fuel consumption (kg/yr), E_{gen} is total annual electrical generation (kWh/yr), H_{gen} is thermal energy (MJ), LHV_{fuel} is lower heating value of fuel (MJ/kg), 3.6 is conversion factor for 1kWh=3.6 MJ.

iv) Battery Storage (BS): Discover 12VRE-3000TF-L (3 kWh), tubular flooded lead-acid battery with a capital cost of INR 22000/unit and O & M cost of INR 700/year is used as storage. Various parametric details of the battery have been reported in [160], [161], and [165]. The required battery capacity B_{cap} (Ah) is given as [161]:

$$B_{cap} = \frac{E_{L(\text{Ah})} D_A}{DOD_{\max} \eta_{temp}} \tag{22}$$

where, E_L is load consumption (Ah), D_A is battery autonomy, DOD_{max} is maximum battery depth of discharge and η_t is battery temperature correction factor. The charging or discharging of battery bank is difference of power generated and load at the time t is given as [161],

$$E_B(t) = E_B(t-1)(1-\sigma) + (E_G(t) - E_{\text{Ld}}(t)/\eta_{\text{inv}})\eta_B \tag{23}$$

where, E_B(t) and E_B(t-1) are charge quantities at time t & (t-1), σ is hourly battery self-discharge rate, E_G is total generated energy by renewable source, E_{Ld} is load demand at time t, η_{inv} and η_B are inverter and battery charging efficiency.

v) Converter (CONV): A 1 kW bidirectional converter with a capital cost of INR 10000 [49], [154], [155], [157]. Current converter technology is free from any maintenance with higher life expectancy, the O & M cost is zero.

vi) Grid: State Electricity Board, under Department of Power, Government of India supplies the electricity to the village at an approximate rate of INR 4.5/kWh. However, the supply is equipped with frequent outages and is highly unreliable. The distribution station is located very near to the village, and no proper data regarding the grid outages is present. Depending upon the inputs from the local people and study of the grid outage timings for approximately one month, the outage data is created to design the unreliable grid. The details regarding the grid outage is given in *the supplementary material (section B, Table B.1)*. Due to unavailability of real-time sell back rates, a rate of INR 2.5/kWh is assumed as sell back rate to the grid.

vii) Key analysis parameters for simulation: An inflammation rate of 5.71 %, a nominal discount factor of 10.70 %, project lifetime of 10 years and a system fixed the cost of INR 500000 is considered for the analysis [159], [160]. The meteorological data are taken from the resource database of NASA [166].

viii) Microgrid Architectures: A total of 17 microgrid designs are framed for the analysis. Specific details are illustrated in Appendix (Table 16). The cost of suitable converters needed by energy sources for connecting to AC or DC bus has been already included in their capital cost. For carrying out the technical and financial analysis, an industry grade software HOMER PRO (commercial version) is used for the analysis. Recently, HOMER PRO has been included with a multiyear analysis tool which can include yearly load growth while designing energy system [161]. As mentioned earlier in sub-section II.C, a new multiyear scalable approach is proposed for the analysis. To show the effectiveness of the proposed method (which is carried out following the steps laid in sub-section II.C using HOMER software), a comparative analysis of the results obtained is carried out with the in-built multiyear approach of the HOMER.

2) ANALYSIS USING PROPOSED MULTIYEAR APPROACH

Utilizing the proposed methodology (sec.II.C, Figure 3) using various parameters values as specified in sub-section III.E.1, simulation is run for different architectures for the energy alternatives. Optimal sizing result of first energy alternative (PVW) in the first architecture (i) (as illustrated in Appendix, Table 16) is shown in Table 9. As shown in Table 9, the size of PV and converter are fixed for all the years. The energy system is scaled up two times in a period of 10 years of project lifetime.

The initial system can meet the load demand for three years excluding the starting year successfully. The first upgrade has to be done to meet the projected load demand of 2019 as highlighted in bold in Table 9 followed by a final update in 2022. In 2019, 25 wind turbines and 500 batteries are added to the existing system followed by addition of 500 more batteries in 2022. The wind turbine is upgraded only once, but the battery is updated twice as it is more economical and easy.

The various costs involved are calculated using HOMER software for individual years, and the same has been presented in Table 9. The specific details how HOMER performs these calculations are detailed in its manual [161]. The final costs are calculated using equation (2) – (5) as given in sub-section II.C. The total *CC* of PVW in first microgrid

TABLE 9. Proposed scalable multiyear basedoptimal sizing of PVW in microgrid architecture (i).

Sl. No.	Year	PV (kW)	WT 10 kW each (Numbers)	BS (Numbers)	CONV (kW)	*CC* in INR (millions)	*NPC* in INR (millions)	*O & M* in INR (millions)	*COE* in INR/kWh
1.	**2015**	**1000**	**25**	**800**	**500**	91.097	9.843	1.317	32.17
2	2016	1000	25	800	500	0.000	1.317	1.317	3.99
3	2017	1000	25	800	500	0.000	1.317	1.317	3.7
4	2018	1000	25	800	500	0.000	0.132	1.317	3.43
5	**2019**	**1000**	**25+ 25 = 50**	**800+500 = 1300**	**500**	26.495	4.403	1.823	10.62
6	2020	1000	50	1300	500	0.000	1.823	1.823	4.07
7	2021	1000	50	1300	500	0.000	1.823	1.823	3.78
8	**2022**	**1000**	**50**	**1300+500 = 1800**	**500**	11.000	2.707	1.601	5.14
9	2023	1000	50	1800	500	0.000	2.061	2.061	3.67
10	2024	1000	50	1800	500	0.000	2.061	2.061	3.4
Cost Summary (All the cost is in Indian National Rupees, INR)						128.592	27.484	16.458	7.40

TABLE 10. Optimal sizing and cost summary of PVW in microgrid architecture (i) obtained by HOMER inbuilt.

	Components			
Sizing	PV (kW)	WT (10 kW Each) (Numbers)	BS (Numbers)	CONV (kW)
	1000	50	2000	500
Cost	*CC* in INR (million)	*NPC* in INR (million)	*O & M* in INR (million)	*COE* (INR/kWh)
	132.992	109.292	17.522	30.44

architecture (i) is INR 128.592 million with an *NPC* and *O & M* costs of INR 27.484 million and INR 16.458 million respectively.

3) ANALYSIS USING IN-BUILT MULTIYEAR APPROACH BY HOMER

Using exactly similar simulation parameters as specified in sub-section III.E.1, the multiyear growth based study with in-built option in HOMER is carried out. The optimal size and the cost specific details are given in Table 10. The size and costs obtained using the in-built approach are more as compared to the proposed multiyear approach. The system configuration obtained from the in-built HOMER approach is same till the project lifetime (10 years for this case). However, in proposed approach, the system is upgraded depending upon the load demand.

4) COMPARATIVE ANALYSIS BETWEEN THE PROPOSED AND IN-BUILT MULTIYEAR APPROACH USING HOMER

The comparative cost illustration is depicted in Figure 8 (a-b). As seen in Figure 8 (a), *CC*, *NPC*, and *O & M* costs are less using the proposed approach as compared to the in-built approach. Especially the *NPC* of the system with proposed approach is very less as compared to in-built approach. The *NPC* and *COE* in the case of the proposed approach are relatively small as compared to in-built approach. The proposed scalable sizing method gives a lower system cost as compared to the in-built HOMER method hence resulting in a low-cost system. The small difference is there in *CC*, and *O & M* costs. The *COE* of the system is INR 30.44 in the case of the in-built method which is very high compared to INR 7.40 calculated using the proposed approach as can be seen in Figure 8 (b).

As illustrated in Figure 9 (a), the load served profile are exactly similar for both the approaches. This shows clearly that, the size of PVW obtained from proposed multiyear method can also meet the growing load demand very effectively with lower cost as compared to the optimal size obtained from in-built multiyear HOMER approach. Figure 9 (b-e) shows the comparison of the system on electrical parameters (total electrical energy production, renewable fraction, PV energy production, and wind energy production and battery losses on a yearly basis) over the project lifetime of ten years (2015-2024).

As seen from the Figure 9 (a-e), the results from the proposed multiyear approach are almost similar to the in-built multiyear approach of HOMER. The proposed scalable system technical performance is as good as the in-built system. A slight variation in total electrical energy production can be observed in Figure 9 (b), which is due to oversizing in the case of in-built HOMER approach. The renewable fraction and PV energy production are also similar as shown in Figure 9 (c) & (d). The electrical energy production from the wind turbine as shown in Figure 9 (e), slightly varies in case of the proposed approach till the year 2018 and then becomes similar from 2019. This variation is due to oversizing of the wind turbine in case of in-built approach from the year 2015 itself. However, in the case of the proposed approach, wind turbines are upgraded depending upon the load growth in 2019. The annual battery losses in case of the proposed approach are

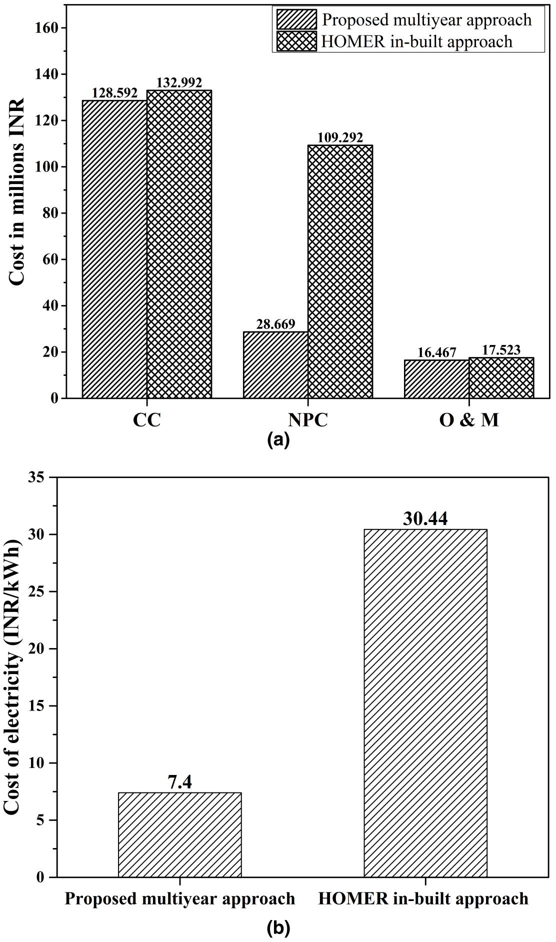


FIGURE 8. Comparative illustration of various costs of PVW obtained using proposed multiyear and HOMER in-built approach. (a) CC, NPC and O & M Cost. (b) Cost of Electricity.

slightly more from 2015 to 2018 as due to less number of batteries as compared to in-built approach which has more number of batteries as illustrated in Figure 9 (f). However, the battery losses become almost similar from the year 2019 as illustrated in Figure 9 (f) which occurs due to the calculation and approximation performed by HOMER upon the upgradation of the number of batteries from 800 to 1300 in the year 2019 and 1800 in the year 2020 as shown in Table 9. The total and individual electrical energy production from the RETs as shown in Figure 9. (b), (d) and (e) is the sum of the electrical energy produced over the year. HOMER always takes into the account of 8760 hours (one year) to run the simulations and gives the results. The detailed explanation has been reported in several studies [45], [50]–[53], [55], [56], [99]–[101], [105]. The PV mean output power is 162.13 kW with both the approaches as calculated by HOMER.

Also, the wind turbine (WT) mean power output is approximately 36.53 kW over the project lifetime using the in-built HOMER approach. With the proposed multiyear approach, WT mean output is 18.26 kW till 2018 and 36.53 kW from 2019 till project lifetime which increases due to upgradation of number of WTs from 25 (2015-18) to 50 (2019-24) as shown in Table 9. So all the results show that the scalable system with the proposed multiyear approach can meet the yearly load demand with a minimum cost as compared to the system from the in-built multiyear approach. Similarly, all the other energy alternatives with specified microgrid architectures as shown in Table 16 are simulated using both the methods (proposed and in-built). The comparative graphical analysis of rest energy alternatives is illustrated in *supplementary material (Section C).*

5) FINAL OPTIMAL SIZING AND COSTING OF THE SYSTEM

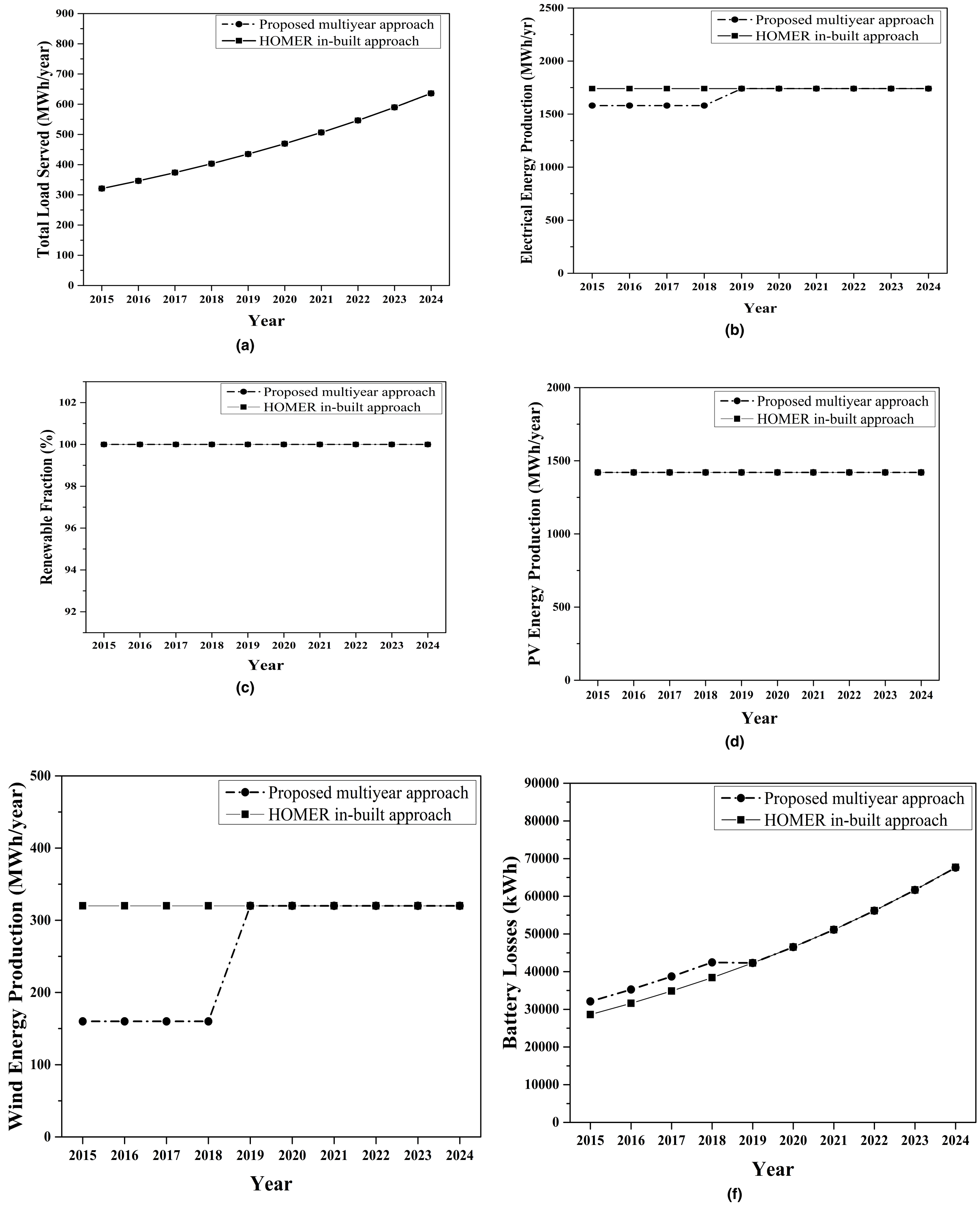
Simulation is run using HOMER PRO, and following optimal size of various components for six energy systems using the 17 architecture as depicted in Table 16 (Appendix) are obtained by the proposed and in-built approach. It can be seen in Table 11, except WDG other five options have six alternatives (3 with proposed sizing approach and 3 with in-built approach). In the case of the proposed sizing method, the final optimal size (2024) is only mentioned. An example of scalable proposed sizing approach has already been illustrated very clearly in the previous sub-section III.E.2 based on method presented in sub-section II.C.

Overall, PVW in centralized off-grid mode has the highest renewable fraction followed by PVWDG in both the approaches. WDG in grid connected mode has the lowest renewable portion. All the optimal system thus obtained from both the methods of the six energy systems are capable of meeting the current as well as future load demand very efficiently. The detailed cost summary of all the systems is depicted in Table 12. It can be observed from Tables 11 and 12, considering proposed and in-built approach that, there is a total of 34 alternatives (A1-A34). It is clearly explained in the previous sub-section III.E.4 with a comparative illustration of scientific results, that system obtained using the proposed approach is technically feasible as compared to the system obtained from the in-built multiyear approach. Even, the costing is much lesser in all the cases of the proposed system. All the six energy system with 34 alternatives are capable of meeting the increasing load demand.

Now selecting the best energy system and alternatives (A1-A34) cannot be done in a simple manner by observing technical and economical results. For example, if the RF is considered then PVW in off-grid with alternatives (A1-A6) have the highest RF (100 %), and PVW in grid connected mode with alternative (A13) has the lowest *COE* (0.98 INR/kWh). So, to decide the best energy system and alternative without being biased, decision analysis tool should be used to determine the better set of solutions which is described in the next section.

F. FINAL PROJECT SELECTION USING HYBRID MCDM MODELS (SEC.II.D, STAGE-4 DESIGN)

All the data obtained from the previous analysis from sub-section.III.E is presented to the technical experts and



(a) (b) (c) (d) (e) (f)

FIGURE 9. Comparative illustration of various electrical parameters results of PVW obtained using proposed and HOMER approach. (a) Total load served. (b) Total electrical energy production. (c) Total renewable fraction. (d) Total electrical energy production by PV. (e) Total electrical energy production by WT. (f) Total energy losses by battery storage.

decision makers for their views for deciding the critical indicators for final project selection. Upon the availability of data and counsel of experts, a total of 10 indicators are decided to evaluate the alternatives (A1-A34) and their classification based on the maximum or minimum values sought for alternatives is done as shown in Table 13.

TABLE 11. Optimal sizing of the energy system obtained by proposed multiyear and in-built HOMER approach.

Energy System	Approach (Proposed / In-built)	Alternatives	System Elements							Renewable Fraction (RF) (%)
			PV (kW)	**WT (kW)**	**DG (kW)**	**CONV (kW)**	**BS (Numbers)**	**Grid (Yearly average)**		
								Energy Purchased (kWh)	Energy Sold(kWh)	
PVW	Proposed	A1	1000	500	✗	500	1800	✗	✗	100
	Proposed	A2	1000	400	✗	500	2000	✗	✗	100
	Proposed	A3	1000	300	✗	500	2000	✗	✗	100
	In-built	A4	1000	500	✗	500	2000	✗	✗	100
	In-built	A5	1000	500	✗	500	2200	✗	✗	100
	In-built	A6	1000	400	✗	500	2000	✗	✗	100
PVWDG	Proposed	A7	700	300	300	500	1000	✗	✗	96.7
	Proposed	A8	700	150	150	700	1200	✗	✗	97.8
	Proposed	A9	800	300	300	500	1000	✗	✗	97.8
	In-built	A10	700	300	300	500	1200	✗	✗	98.5
	In-built	A11	700	200	400	700	1400	✗	✗	98.8
	In-built	A12	800	400	300	500	1200	✗	✗	99.1
PVW	Proposed	A13	600	100	✗	500	900	176,656	425,326	80.35
	Proposed	A14	600	100	✗	400	900	180,764	371,169	78.63
	Proposed	A15	600	100	✗	400	900	179,578	378,606	78.95
	In-built	A16	600	100	✗	400	1000	169,127	413,847	80.94
	In-built	A17	600	100	✗	400	1000	171,890	363,311	79.45
	In-built	A18	600	100	✗	400	1000	170,658	370,470	79.77
PVDG	Proposed	A19	800	✗	150	500	900	178716	550211	79.99
	Proposed	A20	700	✗	150	500	1000	182242	445188	77.33
	Proposed	A21	700	✗	150	500	1000	182242	409274	77.32
	In-built	A22	800	✗	200	400	1000	178716	549048	79.51
	In-built	A23	800	✗	300	500	1000	180205	506965	78.59
	In-built	A24	800	✗	300	500	1000	180205	507155	78.61
WDG	Proposed	A25	✗	800	150	500	700	193685	197793	52.96
	Proposed	A26	✗	800	200	500	700	198135	164796	46.41
	In-built	A27	✗	1000	150	400	800	168281	239886	57.64
	In-built	A28	✗	1000	200	400	800	172612	200217	48.65
PVWDG	Proposed	A29	700	200	150	500	600	165598	563341	73.28
	Proposed	A30	700	300	150	400	600	162611	462443	71.8
	Proposed	A31	700	300	150	400	600	160456	519014	73.16
	In-built	A32	500	200	200	500	800	163195	421058	62.3
	In-built	A33	500	200	200	400	800	166715	363844	58.78
	In-built	A34	500	200	200	400	800	154094	478475	65.69

Using a hybrid MCDM model as already explained in sub-section.II.D analysis is carried out. AHP in conjunction with TOPSIS is used. AHP method is used to determine the criteria/indicator weights. The detailed process of AHP has been already explained in sub-section III.C. The criteria comparison matrix and relative weights of criteria's (W_s) obtained after AHP analysis is given in Table 14.

Once the weights of criteria are determined using AHP, then TOPSIS method is utilized as illustrated in the literature [134]–[144]. The TOPSIS method consists of the following steps.

Step 1 (Formulation of Initial Decision Matrix and Compute Normalized Matrix): Formulate an initial decision matrix having a dimension of $m \times n$ (m = total number of alternatives and n = total number of criteria's).

Compute the normalized values to obtain the normalized matrix. The normalized value (nmv_{gh}) is given by,

$$nmv_{gh} = \frac{f_{gh}}{\sqrt{\sum_{h=1}^{m} f_{gh}^2}} \tag{24}$$

Where f_{gh} is the value of the g^{th} criterion function for the alternative $A_h (h = 1, \ldots, m;$ and $g = 1, \ldots, n)$.

Step 2 (Obtain the Weighted Normalized Decision Matrix): Calculate the weighted normalized value v_{gh} as:

$$v_{gh} = w_{s_g} nmv_{gh} \tag{25}$$

where, w_{s_g} = the weight of the criterion g such that,

$$\sum_{g=1}^{n} w_{s_g} = 1 \tag{26}$$

Note: The criteria weights could be determined using MCDM models or tools as deliberated in [28]. In this study AHP method as illustrated in sub-section III.C is used to obtain the criteria weights (specific details in Table 14).

Step 3 (Obtaining the Solutions as Ideal and Negative-Ideal):

- At first classify the defined criteria in to two major groups in such a way that for one type the decision-maker wants to have maximum values (advantage or benefit) among the alternatives and for other the minimum values are better for alternatives.
- In this study, the criteria's EP, RF, BA are taken as benefit class for which maximum values among the alternatives are advantageous. (Details in Table 13)
- For the economic criteria (CC, NPC, O & M, and COE) along with SD, BL and TEM minimal values are sought. (Details in Table 13)

TABLE 12. Cost summary of optimal systems obtained using proposed multiyear and in-built HOMER approach.

Energy System	Approach (Proposed/ In-built)	Alternatives	Capital Cost (millions)INR	Net Present Cost (millions) INR	O & M Cost (millions) INR	COE (INR/kWh)
PVW	Proposed	A1	128.592	27.484	16.458	7.40
	Proposed	A2	126.794	28.507	16.346	7.30
	Proposed	A3	120.596	27.110	15.489	7.00
	In-built	A4	132.992	109.292	17.522	30.44
	In-built	A5	131.194	107.471	17.456	29.93
	In-built	A6	126.794	104.788	16.680	29.19
PVWDG	Proposed	A7	87.195	28.310	13.903	6.73
	Proposed	A8	87.195	25.100	13.919	6.27
	Proposed	A9	92.496	25.806	14.519	6.52
	In-built	A10	91.595	83.160	12.623	23.16
	In-built	A11	93.297	83.453	12.276	23.24
	In-built	A12	103.094	90.848	13.248	25.3
PVW	Proposed	A13	61.799	8.554	3.223	0.98
	Proposed	A14	61.799	9.449	3.780	1.23
	Proposed	A15	61.799	9.253	3.958	1.19
	In-built	A16	63.999	47.580	3.074	7.00
	In-built	A17	63.999	48.775	4.143	7.61
	In-built	A18	63.999	48.564	39.772	7.51
PVDG	Proposed	A19	69.452	17.510	8.088	1.84
	Proposed	A20	66.351	19.645	10.109	2.29
	Proposed	A21	66.351	19.591	10.056	2.29
	In-built	A22	71.402	60.413	8.759	7.7
	In-built	A23	73.902	63.541	10.351	8.45
	In-built	A24	73.902	63.781	10.633	8.48
WDG	Proposed	A25	71.234	70.790	45.797	11.35
	Proposed	A26	69.784	81.700	53.188	13.60
	In-built	A27	85.830	121.526	43.880	22.29
	In-built	A28	86.580	142.272	57.902	27.66
PVWDG	Proposed	A29	68.947	51.559	28.972	5.27
	Proposed	A30	75.145	52.638	29.747	5.815
	Proposed	A31	75.145	51.845	29.253	5.55
	In-built	A32	64.497	113.202	46.326	16.51
	In-built	A33	63.497	114.729	47.848	17.89
	In-built	A34	74.995	116.175	4.872	15.91

Once criteria are classified, the ideal (A^*) and negative-ideal solutions (A^-) can be obtained as:

$$\begin{aligned} A^* &= \{v_1^*, \ldots\ldots, v_n^*\} \\ &= \left\{\left(\max_h v_{gh}/g \in G'\right), \left(\min_h v_{gh}/g \in G''\right)\right\} \qquad (27) \\ A^- &= \{v_1^-, \ldots\ldots, v_n^-\} \\ &= \left\{\left(\min_h v_{gh}/g \in G'\right), \left(\max_h v_{gh}/g \in G''\right)\right\} \qquad (28) \end{aligned}$$

Where, G' = Criteria's whose maximum values are sought (EP, RF and BA for this study).

G'' = criteria's associated with the minimum values (CC, NPC, O & M, COE, SD, BL and TEM).

Step 4 (Computation of the Separation Measures for All the Alternatives):

Calculate the separation measures of all the alternatives using the ideal and negative ideal solutions obtained from the previous step.

From the ideal solution the separation measure (S_h^*) of each alternative can be calculated as,

$$S_h^* = \sqrt{\sum_{g=1}^{n}\left(v_{gh} - v_g^*\right)^2} \qquad (29)$$

TABLE 13. Performance indicators/criteria's and their classification for final selection of alternatives.

Sl. No.	Criteria		Sub-Criteria	Classification of indicators based on higher / maximum or lower / minimum values sought for alternatives evaluation	
1.	Technical	I.	Total Electrical Energy Production (EP)	Maximum value	↑
		II.	Renewable Fraction (RF)	Maximum value	↑
		III.	Battery Autonomy (BA)	Maximum value	↑
		IV.	Storage Depletion (SD)	Minimum value	↓
		V.	Battery Losses (BL)	Minimum value	↓
2.	Economic	VII.	Total Capital cost (CC)	Minimum value	↓
		VII.	Total NPC (NPC)	Minimum value	↓
		VIII	Total O & M Cost (O &M)	Minimum value	↓
		IX	Cost of electricity (COE)	Minimum value	↓
3.	Environmental	X.	Total Emissions (TEM)	Minimum value	↓

TABLE 14. Criteria comparison matrix (criterion *x* criterion) obtained using AHP method.

	EP	RF	BA	SD	BL	CC	NPC	O &M	COE	TEM	W_s
EP	1	1	1	5	5	1	1	1	1	1	.132
RF	1	1	1	3	3	1	1	1	1	1	.111
BA	1	1	1	1	1	3	1	3	3	1	.141
SD	.2	.3	1	1	1	.5	1	.5	.5	1	.058
BL	.2	.3	1	1	1	.5	1	.5	.5	1	.062
CC	1	1	.3	2	2	1	1	1	1	1.	.092
NPC	1	1	1	1	1	1	1	5	1	1	.117
O & M	1	1	.3	2	2	1	.2	1	1	1	.084
COE	1	1	.3	2	2	1	1	1	1	5	.121
TEM	1	1	1	1	1	1	1	1	0.2	1	.0822
Consistency Ratio (CI) = 0.0889											

TABLE 15. Final composite score and rankings of energy alternatives obtained after using TOPSIS method.

Energy System	Approach (Proposed/ In-built)	Alternatives	Final composite score	Final Ranking
PVW	Proposed	A1	0.7050	14th
	Proposed	A2	0.7314	12th
	Proposed	A3	0.7313	13th
	In-built	A4	0.3497	30th
	In-built	A5	0.3579	29th
	In-built	A6	0.3750	28th
PVWDG	**Proposed**	**A7**	**0.8054**	**9th**
	Proposed	**A8**	**0.8303**	**7th**
	Proposed	**A9**	**0.8253**	**8th**
	In-built	A10	0.5245	22nd
	In-built	A11	0.5219	23rd
	In-built	A12	0.4721	25th
PVW	**Proposed**	**A13**	**0.9674**	**1st**
	Proposed	**A14**	**0.9648**	**2nd**
	Proposed	**A15**	**0.9650**	**3rd**
	In-built	A16	0.7617	10th
	In-built	A17	0.7536	11th
	In-built	A18	0.6369	21st
PVDG	**Proposed**	**A19**	**0.9212**	**4th**
	Proposed	**A20**	**0.9044**	**6th**
	Proposed	**A21**	**0.9049**	**5th**
	In-built	A22	0.6772	15th
	In-built	A23	0.6543	18th
	In-built	A24	0.6523	19th
WDG	Proposed	A25	0.5141	24th
	Proposed	A26	0.4335	26th
	In-built	A27	0.2505	33rd
	In-built	A28	0.1714	34th
PVWDG	Proposed	A29	0.6640	16th
	Proposed	A30	0.6498	20th
	Proposed	A31	0.6559	17th
	In-built	A32	0.3243	31st
	In-built	A33	0.3173	32nd
	In-built	A34	0.4298	27th

Similarly, from the negative-ideal the separation measure (S_h^-) is given as,

$$S_h^- = \sqrt{\sum_{g=1}^{n} \left(v_{gh} - v_g^-\right)^2} \tag{30}$$

Step 5 (Determine the Relative Closeness to the Ideal Solution for Each Alternative): The relative closeness (C_h^*) of the alternative to the ideal solution can be computed using following equation,

$$C_h^* = \frac{S_h^-}{\left(S_h^* + S_h^-\right)} \tag{31}$$

Note: The relative closeness value is between 0 and 1, with 0 being the worst possible and 1 the best possible solution.

Step 6 (Determine the Preference Order): Arrange all the alternatives based on the descending order of the relative closeness value (C_h^*) and assign the ranking positions. The alternative having the first rank (maximum value) is proposed as best solution.

It is evident from the Table 15 (in bold highlighted), all the top best scores of the alternatives obtained are from the proposed multiyear approach which proves once again the effectiveness of the proposed scalable sizing method. Energy system PVW (grid connected) ranks the top position ($1^{st} - 3^{rd}$) with microgrid architectures (vii-ix). The second energy system position ($4^{th} - 6^{th}$) is taken by PVDG (grid connected) in microgrid architectures (x, xii, and xi) followed

TABLE 16. Detailed list of microgrid architectures considered for feasibility analysis.

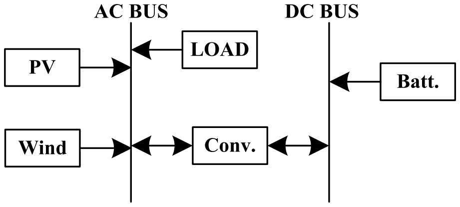
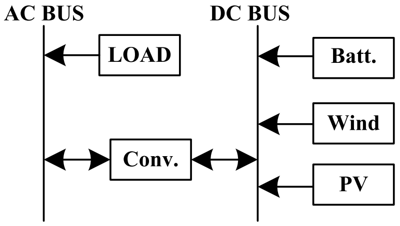
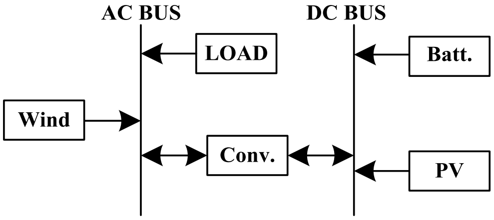
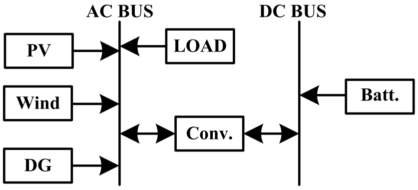
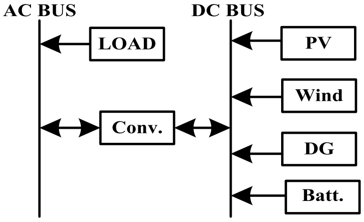
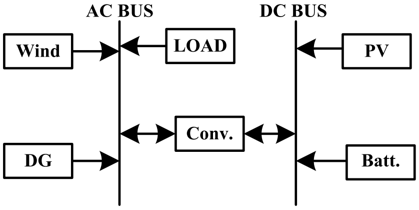
S. N.	Alternative	Elements						Configuration	Nos.	Architecture
		PV	Wind	DG	Conv.	Batt.	Grid			
1.	PVW	✓	✓	✗	✓	✓	✗	Off-grid	(i)	
		✓	✓	✗	✓	✓	✗		(ii)	
		✓	✓	✗	✓	✓	✗		(iii)	
2.	PVWDG	✓	✓	✓	✓	✓	✗	Off-grid	(iv)	
		✓	✓	✓	✓	✓	✗		(v)	
		✓	✓	✓	✓	✓	✗		(vi)	

TABLE 16. ***(Continued.)*** **Detailed list of microgrid architectures considered for feasibility analysis.**

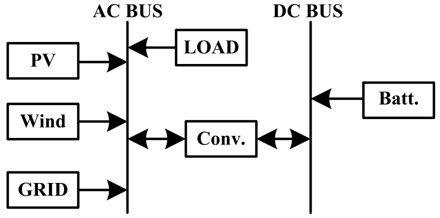
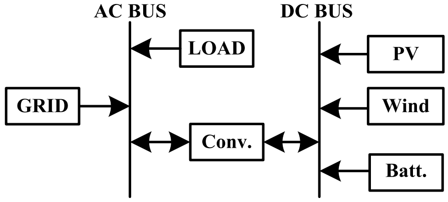
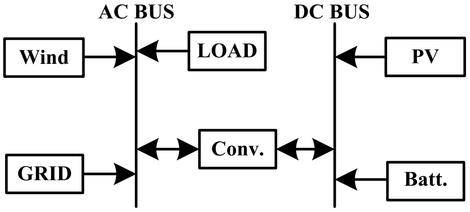
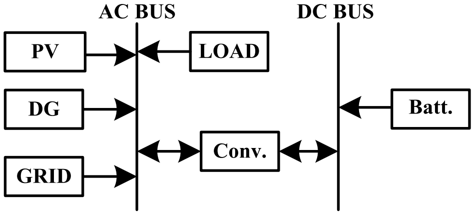
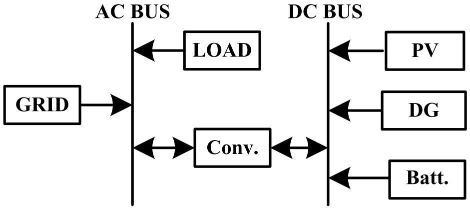
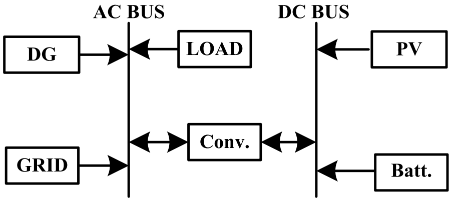
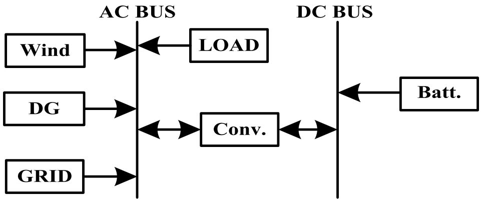
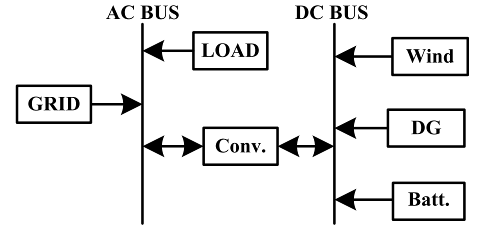
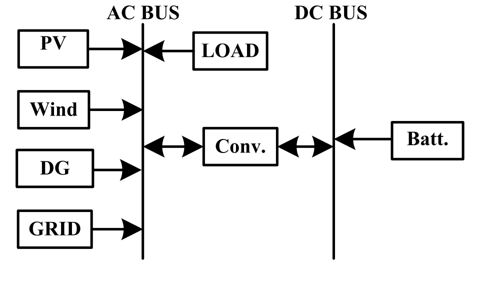
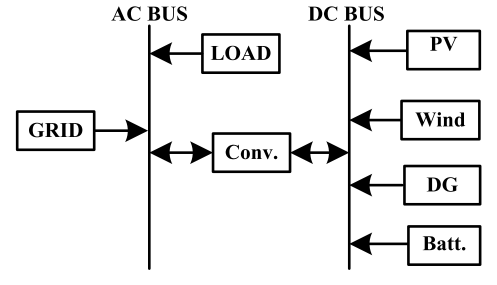
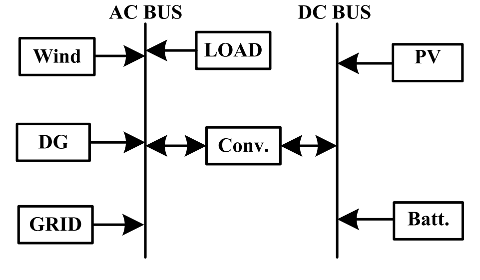
3.	PVW	✓	✓	✗	✓	✓	✓	Grid	(vii)	
		✓	✓	✗	✓	✓	✓		(viii)	
		✓	✓	✗	✓	✓	✓		(ix)	
4.	PVDG	✓	✗	✓	✓	✓	✓	Grid	(x)	
		✓	✗	✓	✓	✓	✓		(xi)	
		✓	✗	✓	✓	✓	✓		(xii)	
5.	WDG	✗	✓	✓	✓	✓	✓	Grid	(xiii)	

TABLE 16. *(Continued.)* Detailed list of microgrid architectures considered for feasibility analysis.

		✗	✓	✓	✓	✓	✓		(xiv)	
6.	**PVWDG**	✓	✓	✓	✓	✓	✓	**Grid**	(xv)	
		✓	✓	✓	✓	✓	✓		(xvi)	
		✓	✓	✓	✓	✓	✓		(xvii)	

by PVWDG (off-grid connected) in microgrid architectures (v, vi and iv) respectively. So, a set of possible solutions is obtained based on the final scores.

All the possible solutions obtained are capable of fulfilling the load requirements of the target village in a particular microgrid architecture. As already outlined in section II, the solutions are judgmental in nature, and it should be presented to the group of experts and decision makers involved in the project to select the best option and architecture. Also, specific government regulated policies and financing outlook has to be considered before choosing one of the alternatives from the set of solutions obtained.

IV. CONCLUSIONS

This paper proposes a novel and simple framework for designing a rural sustainable microgrid for developing nations considering increasing load scenario. The framework also includes a new, simple yet very effective method for techno-financial analysis of the energy system. The proposed scalable multiyear load growth based techno-economic method is verified by comparing with the in-built multiyear approach of HOMER PRO and the results shows that the proposed approach is more efficient. The results obtained after implementation from the case study correctly points out the importance of considering not only technical and economic aspects but also social and environmental issues. When scenarios are considered, a set of solutions with the different scores for the same alternatives are obtained as observed in the results during the first level of decision making. By using the scalable approach presented in this work, the over and under sizing of the micrograms would be avoided and the cost will be reduced when yearly load growth is considered. The notions outlined in this work put forth a detailed and straightforward roadmap for rural electrification using sustainable microgrids utilizing local energy resources. The assessment illustrated in this work shows that the scientific procedures when employed to provide real-time evaluation considering real situations for rural electrification in an efficient manner would certainly avoid project failures. In future research work, the framework could be extended to the component level design, accommodating more number of scenarios, criteria and alternatives not only for rural locations at disintegrated levels but also for sustainable microgrid design for cities considering climatic variations.

APPENDIX

See Table 16.

ACKNOWLEDGMENTS

The authors are grateful to all the experts who give their valuable inputs in conducting this research. Authors especially express their gratitude to Mr. K. K. Singh, CEO, Brawn Energy Pvt. Ltd, India and his team of experts for their suggestions and sharing the field experience to make this work as real as possible. Authors also extend their warm gratitude towards the Er. S. K. Tyagi (State Public Work Department), Er. Nabam Epo Hina (State Power Department), Er. Alok Singh Bishen (Sr. Project Engineer, Om Metals Infraprojects Ltd) and experts from private power organizations working in Papumpare region for their overwhelming support. Special thanks to Mr. Chera Taring, a local leader from the Leporiang village for his endless support for past five years in helping us to understand the community and collection of data. Without his constant support, this research would not have been possible.

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