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Research Article

A Novel Design, Economic Assessment, and Fuzzy-Based Technical Validation of an Islanded Microgrid: A Case Study on Load Model of Kibber Village in Himachal Pradesh

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Rural and remote area electrification is of grave concern around the globe. Therefore, well-planned and cost-effective microgrids integrating renewable energy sources are emerging as effective solutions. However, the microgrid's stable operation and its future deployment is affected by the perturbations caused due to uncertainity in renewable sources, dependency on the battery state of charge, and load variation. So, considering the possible concerns affecting the planning and development of a microgrid for any given region, this paper proposes a comprehensive performance assessment of the hybrid residential microgrid based on a load model of Kibber village in Himachal Pradesh, India. The proposed approach is divided into three parts for the best planning of microgrids. Firstly, the MATLAB–Simulink software technically analyzes the system performance under perturbations considering the available renewable sources. Secondly, an economic analysis using HOMER Pro software is done to examine the cost-effectiveness of the proposed microgrid model through the simulation of electrical loads for Kibber village, considering the available renewable sources. Lastly, a real-time analysis of the proposed prototype of programmable logic controller-based hardware test bench has been developed, aiming for future regional microgrid deployment. System voltage, frequency, power shared, percentage of load met, energy cost, available renewable energy resource, etc. have been considered for validating the proposed controller. The proposed comprehensive assessment of the microgrid model is reproducible with necessary modifications for any geographical location. It will be helpful for its future deployment aiming at rural and remote electrification.

1. Introduction

Rural and remote region electrification is an integral component of poverty mitigation, rural growth, and socioeconomic development, especially in India. It supports the region's growth by providing reliable and continuous electricity for residential and commercial needs [1, 2]. In view of this, MG for rural and remote areas is a favorable solution with technological development and capacity to integrate renewable energy sources (RESs). However, the critical concern related to rural area electrification via MG includes its optimal design, planning, and assessment considering the available resources and consumer demand [3, 4]. Under such a concern, the techno-economic feasibility analysis has been coined as a favorable solution in the literature [4]. This analysis uses various factors to calculate the possible combination of resources for the given location while considering the system cost, available resources, type and total load demand, type of integrated storage, and mode of MG operation. Previously, several pieces of research around the globe have been carried out for MG system feasibility analysis. A detailed investigation based on single RES with ESS has been done for the developed system considering the percentage of renewable penetration, cost of energy (COE), and carbon emissions as effective parameters [5]. Besides, the design optimization and feasibility analysis of the PV-wind-fuel cell-based MG model developed using HOMER (hybrid optimization model for multiple energy resources) Pro software are presented in [6]. The investigation includes the effect of different MG operation modes and the ESS's presence on MG economics.

The impact of optimal resource sizing on islanded MG's financial and sensitivity analysis has been discussed in [7]. A feasibility analysis of PV-diesel generator-flywheel-based MG for the remote location of Saudi Arabia has been presented in [8]. Using the HOMER Pro software, the impact of ESS on the system economics and the effect of diesel generators (in coordination with RESs) on the environment have been investigated. A biomass-gasifier-based MG system has been investigated using HOMER software in [9], aiming at a minimum (0%) unmet load condition. The analysis shows a high reduction in environmental impact but a hike in capital investment and COE.

Similarly, a PV and biomass-based MG model with an agricultural farm and a residential community load has been investigated in [10]. The off-grid MG model is analyzed based on per-unit cost and its payback period. Multiple MG models and combinations have been studied in [11]. The work presents (PV)/battery and PV/battery/fuel cell (FC) power-based models, where the analysis is done per the initial cost, operating cost, and COE. The PV/hydro/diesel and battery-based systems have been analyzed using the HOMER Pro software [12]. The work presents different scenarios where the system's performance assessment and sensitivity analysis have been done. Besides, a summary of previous research articles discussing HOMER Pro software's assessment aspects and application for different RESs combinations in the Indian locations are tabulated in Table 1.

From the observation, the critical parameters identified for the MG's overall planning and feasibility analysis include the availability of RESs, different storage options, load conditions, and specific geographical locations. The other aspects of comprehensive MG assessment include technical simulation and hardware validation of the planned MG model using various simulation tools and laboratory setups. These aspects are essential from the validation point of view. In the case of MG deployment, simulation validation plays a crucial role in understanding the system's behavior under uncertain conditions [28–30]. For this purpose, the MATLAB simulation-based platform proves advantageous where the MG system can be simulated under standard and uncertain test conditions. Herein, the MATLAB–Simulink platform offers the advantage of simulating the planned MG model to perform technical analysis. It allows for the simulation of the system under uncertain conditions and in the presence of a controller, wherein the performance can be assessed [31, 32].

Furthermore, the decision to stabilize MG's operation relies on technical performance analysis, including the system's electrical parameters, for example, system voltage, frequency, power sharing between resources [33, 34]. In continuation, the other shortcoming in the previous state-of-the-art research is the implementation assessment of the planned MG model. In the case of MG deployment, testing the planned MG and its behavior analysis in the presence of the actual controller is of utmost importance. It tests the control logic designed for the planned MG and allows for the analysis of the performance of the actual controller in real time. Henceforth, the research gaps are presented below by combining the literature survey from Table 1.

(i) The solar, wind, and battery-based MG feasibility analysis for the remote regions of Himachal Pradesh, India, has not been very well explored. Specifically, such regions expect a very high renewable potential and thus need special attention. Notably, the details of MG feasibility for such regions are not available in the present state-of-the-art literature.

(ii) Economic analysis based on COE, NPC, f_{ren}, emissions, component sizing, and unmet load percentage has not been thoroughly explored for an islanded solar, wind, and battery-based MG for rural and remote regions of India. Such regions possess high renewable potential but lack proper analysis.

(iii) The technical assessment of the proposed MG via simulations in the present literature has not been well explored. It is such that the reliability and security of the planned MG, especially for a specific geographical location and conditions, for example, uncertain or bad weather, are not well discussed.

(iv) After analyzing the economic and technical aspects with a robust controller for stable operation and control, implementing a well-planned MG at the given location is of great concern. The feasibility analysis does not present the real solution to this problem of implementation assessment. Therefore, the ideology of presenting a robust controller for such an issue in real-time rural and remote locations is not well explored.

(v) Based on the facts and conclusive evidence, the policy recommendations must be addressed appropriately, considering the comprehensive feasibility results.

Thus, based on the summary above of the existing state-of-art literature and the research gaps, the critical points of the proposed work are presented in Table 2.

Henceforth, in this work, we propose an optimal design for islanded MG for Kibber village, India, considering only high-potential solar and wind-based RESs. Notably, other resources available for the location include biomass and hydro. However, only solar and wind were considered for the available potential, feasibility, and economic aspects. Assessment of the designed MG system has been proposed as shown in Table 2. It includes economic assessment using HOMER Pro software, and technical assessment using MATLAB–Simulink. The technical evaluation was simulated considering uncertainties in renewable energy resources aiming at stable MG operation. Implementation assessment using a PLC-based robust and real-time controller including system performance analysis has been performed through a testbench prototype. Henceforth, the proposed research contributes to the previous state-of-art literature given the different aspects of MG assessment ("comprehensive assessment"), i.e., economic, technical, and implementation

Table 1: Summary of existing work—Indian scenario.

System design	Location	Assessment aspects	Remarks
Wind-PV-battery-grid [13]	Haryana, India	(1) Economic feasibility	(1) Economic analysis of proposed MG for a given geographical area (2) Technical assessment using MATLAB has been done for power sharing between different sources
PV-wind-diesel-battery [14]	Punjab, India	(1) Economic feasibility	(1) Assessment of multiple locations in Punjab for comparative analysis (2) Comparison between different combinations of sources, from which the significance of PV in the northern region of India has been highlighted (3) Consideration of 1.3 kW telecommunication load as critical load
PV-battery-grid [15]	Punjab, India	(1) Economic feasibility	(1) High renewable potential in northern India (2) There is an inverse relationship between the level of renewable energy output and COE for the designed system
PV-battery-grid [16]	Uttar Pradesh, India	(1) Economic feasibility (2) CO_2 emissions (3) Technical assessment with DSM	(1) Mpact of grid availability on COE (2) RES optimization for satisfying the daily load demand (3) DSM of developed MG with NCL shed/shifted towards available solar or battery energy sources (grid satisfying critical load)
PV-wind-biomass-battery [17]	Pondicherry, India	(1) Techno-economic Analysis (2) net present cost (NPC) analysis (3) load growth assessment	(1) Predicted load growth using the ANN-LM technique (2) Islanded MG as a cost-effective solution for rural electrification (3) Reduced system emission and optimized system with ANN-LM (4) Biomass as a critical contributor to renewable fraction (f_{ren}) and reliable power supply
PV-wind-biomass [18]	Madras, India	(1) Economic Feasibility (2) optimal component sizing	(1) HOMER Pro tool for techno-economic analysis and MG planning (2) Review of HOMER Pro for MG design and simulation (3) Effective use of available RESs for electrification (4) COE as a significant parameter in overall system analysis
PV-wind-hydro-gen.-battery [19]	Gujarat, India	(1) Economic Feasibility (2) reduced carbon emissions (3) urban electrification	(1) High renewable contribution for optimal MG planning (2) Economical results with a higher number of RESs with reduced emissions (3) Higher capital cost leads to an overall increase in other economic parameters
PV-wind-hydro-biomass-battery [20]	Uttarakhand, India	(1) Economic feasibility (2) Reliability analysis (3) Technical assessment with DSM	(1) Islanded MG for remote and rural region electrification with wind as the dominant resource (2) Economic assessment and DSM analysis for the designed MG system (3) Biomass as a reliable RESs can only be used for high availability locations, which increases system economics
PV-wind-diesel gen.-Battery [21]	Punjab, India	(1) Economic feasibility (2) Total energy production	(1) Feasibility analysis for different locations in Punjab, India, with available solar as a key contributor (2) RESs combination with the least cost as the most feasible solution from economic aspects (3) COE reduces with high renewable potential
PV-wind-hydro-battery [22]	Tamil Nadu, India	(1) Techno-economic feasibility (2) Environmental aspect	(1) Hydropower source is significant but constrained to the high amount of water resource availability and specific geographical location (2) Wind is a significant RES in coastal regions for higher power generation (3) Higher RESs contribution leads to minimizing carbon emissions
PV-wind-hydro-bio. Battery [23]	Puducherry, India	(1) Techno-economic feasibility (2) Resource assessment	(1) A higher value of f_{ren} leads to a minimum unmet load percentage (2) Islanded MG as a favorable solution for rural and remote villages (3) An abundance of solar and wind energy leads to reduced COE for more than 90% of load hours
PV-wind-hydro-bio. Battery [24]	Chhattisgarh, India.	(1) Techno-economic feasibility (2) Resource assessment 3) Financial and business aspects	(1) Application and combination of different RESs in satisfying multiple types of electric loads. (2) Dependency of component sizing based on peak load demand of the day (3) Discussion on financing challenges, business model, and tariff issues

Table 1: Continued.

System design	Location	Assessment aspects	Remarks
PV-wind-battery-grid [25]	Haryana, India	(1) Techno-economic feasibility	(1) Solar and wind-based RESs with higher potential for satisfying multiple types of electric loads (2) The excessive potential of solar energy in northern India 3) Reduced CO_2 emissions due to higher renewable contribution
Grid-PV-wind-diesel generator [26]	Tamil Nadu, India	(1) Techno-economic feasibility	(1) Use of a diesel generator for enhancing system reliability, however not a suitable option given environmental constraints (2) A significant impact of only RESs-based system on CO_2 emissions and overall system cost (3) An abundance of RESs leads to reduced COE and overall gas emissions
PV-wind-battery-grid [27]	Rajasthan, India	(1) Techno-economic feasibility	(1) Application of RESs to cater environmental pollution (2) Cost-effective solution for increasing power demand in India (3) Applicability of high potential of solar, leading to high system efficiency and low dependency on grid

Table 2: Tabulated summary of proposed work.

System design	Location	Assessment aspects	Remarks
Proposed work	Kibber village, Himachal Pradesh, India	(1) Techno-economic feasibility (2) Technical assessment using simulations (3) Feasibility analysis using PLC-based hardware test bench	(1) HOMER Pro software is used to plan islanded residential MG systems equipped with renewable energy resources per the load demand (2) Economic analysis of various parameters based on system architecture, costs, and system components is performed (3) MG is planned using MATLAB–Simulink software under various uncertain conditions and technically assessed (4) Feasibility and implementation assessment of proposed MG using PLC-based robust controller and developed hardware test bench

assessment aiming for optimal design and planning of islanded MG for the northern region of India.

This paper is organized as follows. Section 2 provides the methodology adopted for the present research. The proposed system's simulation results are analyzed in Section 3. The paper is concluded in Section 4, mentioning the policy recommendations and future scope of research.

2. Methodology

This section presents this research's proposed methodology, including location information, load profile assessment, resource assessment, simulation and optimization tools, and the functional flowchart.

2.1. Location and Site Background. As shown in Figure 1, the site considered in this work is the Kibber village in Spiti valley, Himachal Pradesh state, India, at a longitude 78°0′36.95 "E and latitude 32°19′57.58 "N at an altitude of 4135 m/13566 feet above the sea level. The main reason for selecting such a region is the mass availability of RESs and the high cost of electricity transmission. It is relevant to mention that this location was not visited by the authors physically. However, selecting remote sites using HOMER Pro and satellite imagery information has been used for academic research to investigate the MG feasibility in a remote location. This pre-planning assessment approach of MG's technical and economic feasibility is deemed acceptable as it tends to reduce the R&D cost before the actual site visit.

Figure 1: Geographical view of the investigated site.

According to Census 2011 information on this site, approximately 366 people lived in 77 families/households with 4–7 persons in each house [35]. The main occupation of this 465 hectares village is related to agriculture and small businesses. In addition, this site is considered one of the last motorable villages with low or negligible communication facilities. Because of the high altitude, rough terrain, and limited transportation facilities, maintaining an uninterrupted power supply is a significant challenge. Therefore, under the rural electrification act and aiming toward electrical development, there is a need to propose an MG system at this site to meet the load demand and deliver a reliable power supply.

2.2. Load Profile Assessment. The load demand requirement of the Kibber village has been estimated by considering the number of households and the number of people [35]. It includes various domestic, commercial, and agricultural loads over 24 hours.

The input of estimated load data, considering the number of households and essential electrical appliances, is given to HOMER Pro software [35, 36]. The scaled value of the annual average load per day (kWh/d) is considered. Also, HOMER Pro software evaluates hourly electrical load values by using an hourly load profile and incorporating random variability factors. It can be observed that the load demand is maximum during the morning and evening hours of the day. The load has been categorized as Load#1 (domestic load) and Load#2 (commercial + agricultural load) for the developed model. The data analysis has identified that the peak and daily load demand of Load#1 nursed in HOMER Pro are 18.52 kW and 89.15 kWh/d, respectively. As analyzed, the combined peak load and daily load demand of the Load#2 are 6.53 kW and 41.88 kWh/d, respectively. Figures 2(a) and 2(b) depict the daily, seasonal, and yearly load profiles.

2.3. Resource Assessment. This work considers solar and wind-based RESs and the battery energy storage system for designing the MG model. The data for the considered site of Kibber village in Himachal Pradesh are obtained from the NASA surface meteorology and solar energy database and NREL (National Renewable Energy Laboratory).

2.3.1. Solar Photovoltaic Resource. Solar resource potential is very high at the given location of Kibber, especially in summer. Due to the high altitude, the location experiences a high sky clearness index (CI) and, thus, high solar radiation. The mathematical expression used to calculate the PV power output in HOMER Pro software is presented using equations (1) and (2) [37–39].

$$P_{PV} = Y_{PV} \cdot f_{PV} \cdot \left(\frac{\overline{G}_T}{\overline{G}_{T,STC}}\right)\left[1 + \alpha_P\left(T_C - T_{C,\,STC}\right)\right], \tag{1}$$

$$T_C = \frac{T_a + \left(T_{c,STC} - T_{a,STC}\right)\left(\overline{G}_T/\overline{G}_{T,STC}\right)\left[1 - \eta_{mp,STC}\left(1 - \alpha_p * T_{c,STC}\right)/\tau * a\right]}{1 + \left(T_{c,STC} - T_{a,STC}\right)\left(\overline{G}_T/\overline{G}_{T,STC}\right)\left[\alpha_p * \eta_{mp,STC}/\tau * a\right]}. \tag{2}$$

The solar PV data obtained from NREL for both CI and daily radiation in kWh/m^2/day have been tabulated in Table 3 with other details. Besides, the annual average value of solar irradiance is also mentioned as a part of the tabulated data. As per analysis, the CI varies in the range of 0.538 to 0.699, and global horizontal irradiance (GHI) varies in the range of 2.990 to 7.020 kWh/m^2/day. Lastly, the scaled annual average value of GHI is 5.10 kWh/m^2/day.

2.3.2. Wind Energy Resource. Analogous to solar photovoltaic, wind resource for the considered location has a high potential. With an approximate altitude equal to 4000 m, wind availability is very high and can be utilized to take it as a potential resource. The mathematical expression related to the real power of the wind energy system for each instant of time depends on various parameters. These factors include wind density, wind speed, turbine sweep area, and power coefficient. Correspondingly, the expression for mechanical power output is given by equation (3), wind speed at the particular hub height is calculated as in equation (4), the output power can be expressed in equation (5), and the actual power of the wind turbine is expressed by equation (6).

$$P_{WT} = \frac{1}{2}\rho\pi R^3 C_p(\lambda, \beta)V^3, \tag{3}$$

$$V = V_i\left(\frac{H}{H_i}\right)^x, \tag{4}$$

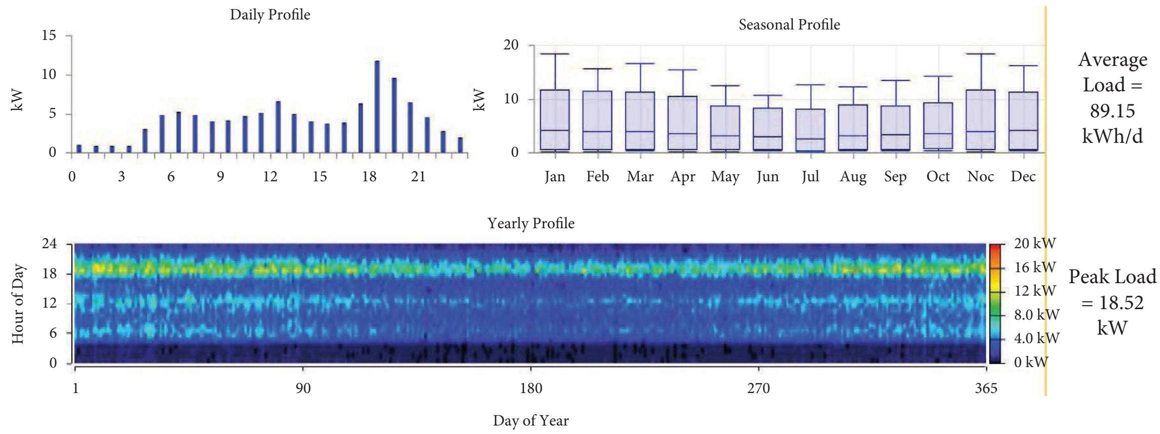
$$P_w = \begin{cases} P_R, & \text{if } V_R < V < V_{c0}, \\ P_{\text{rated}}\left(\dfrac{V^3 - V_{C1}^3}{V_R^3 - V_{C1}^3}\right), & \text{if } V_{C1} < V < V_R, \\ 0, & \text{Otherwise}, \end{cases} \tag{5}$$

$$P_A = P_w A_w \eta. \tag{6}$$

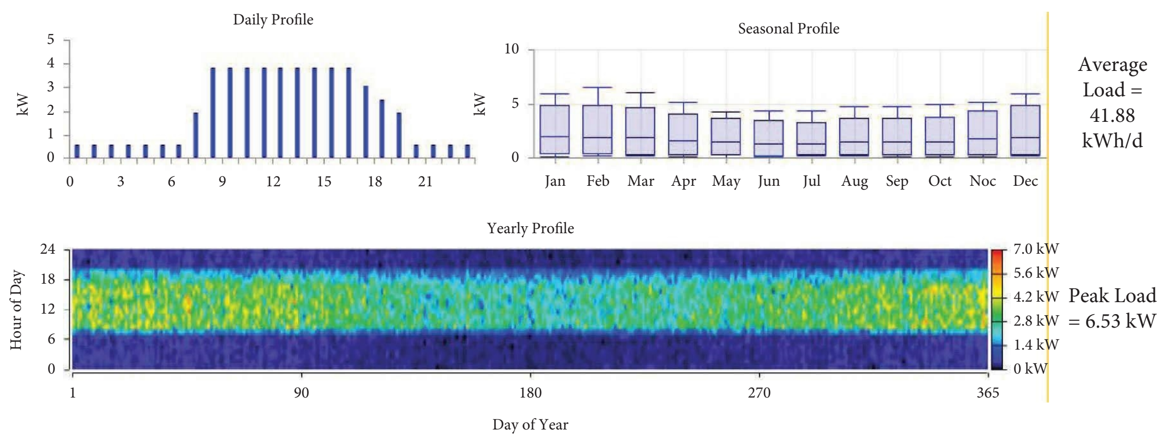
Table 4 shows the monthly average wind speed data, which varies from 5.350 to 8.290 m/s with an annual average wind speed of 7.110 m/s. Notably, the considered height for measuring the wind speed using an anemometer is taken as 50 m. Also, the effects of wind speed variation on system performance can be investigated by performing the sensitivity analysis, depending on the variation in values.

2.3.3. Other Components

(1) Battery Energy Storage System (BESS). The power produced by either of the RESs may not get utilized at every time of the day. Thus, it is highly significant to store the excess energy produced from the RESs in a BESS. In HOMER Pro software, various storage units are available, including a Li-ion battery, flywheel, and fuel cell. The mathematical expressions displaying the battery's storage capacity and state of charge are given in equations (7) and (8).



(a)



(b)

Figure 2: Plots for investigated load profiles. (a) Plots for domestic load profile (Load#1). (b) Plots for commercial and agricultural load profiles (Load#2).

Table 3: Tabulated data for solar photovoltaic energy resources.

Solar radiation data					
Month	CI	Solar radiation	Month	CI	Solar radiation
January	0.573	3.170	July	0.592	6.670
February	0.567	3.860	August	0.589	6.150
March	0.547	4.660	September	0.644	5.820
April	0.538	5.440	October	0.699	5.100
May	0.578	6.420	November	0.663	3.850
June	0.611	7.020	December	0.583	2.990
Minimum: 2.990, maximum: 7.020			Annual average value: 5.10		
Technical and economic data					
Parameter	Value		Parameter	Value	
Pmax	350 W		Capital cost	725 $/kW	
Derating factor	88%		Replacement cost	725 $/kW	
Efficiency	18.90%		O&M cost	10 $/kw/y	
Lifetime	25 years		Operating temperature	≈+85°C	
Technology	Monocrystalline (mono)		Operating current	10.52 A	
Temperature coefficient	−0.390		Operating voltage	33.3 V	
Open circuit voltage	40 V		Short circuit current	11.28 A	

Table 4: Tabulated data for wind energy resources.

Wind speed data			
Month	Wind speed	Month	Wind speed
January	7.960	July	5.600
February	7.890	August	5.350
March	7.580	September	6.090
April	7.010	October	7.440
May	7.200	November	7.970
June	6.900	December	8.290
Minimum: 5.350, maximum: 8.290		Annual average value: 7.110	
Technical and economic data			
Parameter	Value	Parameter	Value
Manufacturer	Generic	Rated capacity (kW)	10
Lifetime (y)	22	Rotor diameter (m)	22
Hub height (m)	24	Tower height (m)	50
Capital cost	\$44500	Swept area (m^2)	2300
Replacement cost	\$40500	Number of blades	3
O&M cost/year	\$400	Cut-in-speed (m/s)	3
Rated wind speed (m/s)	10	Cut-out-speed (m/s)	21

$$P_{\text{batt}}^{\text{Max}} = \frac{N_{\text{batt}} V_{\text{batt}} I_{\text{batt}}^{\text{Max}}}{1000}, \tag{7}$$

$$SOC\ (n) = [SOC\,(n-1) - \Delta SOC\,(n)]. \tag{8}$$

The battery constraints assumed in this work include the following equations:

$$SOC_{\text{Min}} \leq SOC\,(n) \leq SOC_{\text{Max}}, \tag{9}$$

$$SOC_{\text{Min}} = (1 - DOD) * SOC_{\text{Max}}. \tag{10}$$

However, the details of BESS employed in this work are given in Table 5. The prime aim of adding a storage unit into the system is to use it as ancillary support, such as to increase the system's reliability.

(2) Power Converters/Inverters. The AC/DC or DC/AC converters or inverters are the most critical components for designing an MG with different power sources. With such components, all the resources and different types of loads can be interconnected, aiming for smooth integration between resource and load. The converter forms a two-way bus system resulting in the bidirectional power flow, where AC power can be converted into DC for battery charging (as required), and DC power can be converted into AC (acting as an inverter) for the connected electrical load. The configuration details of the power converter used in the present research are tabulated in Table 6, whereas the mathematical expression specifically for inverter sizing is given in the following equation:

$$P_{inv}\,(t) = \frac{P_L^M}{\eta_{inv}}. \tag{11}$$

Table 5: Tabulated data for battery energy storage system.

Parameter	Value
Manufacturer	Discover innovative battery solutions
Efficiency (%)	80
Capital cost (\$)	400
Replacement cost (\$)	330
O&M cost/year (\$)	7
Maximum charge current (A)	43
Internal resistance	5 mΩ
Short circuit	2150
Self-discharge	5%/month
Nominal capacity (kWh)	3.11
Nominal voltage (V)	12
Minimum/Maximum SOC	20% to 80%
Initial SOC	100%
Electrolyte	1.255 SG.
Height	410 mm
Weight	60.8 kg
Maximum capacity (ah)	260
Lifetime throughput (kWh)	3581.60

Table 6: Tabulated data for power converter.

Parameter	Value
Type	AC-DC-AC
Capital cost (\$)	600
Lifetime (years)	18
Replacement cost (\$)	350
O&M cost (\$)	5/year
Efficiency	95%

2.3.4. System Economic Parameters. This subsection discusses the various economic terms and parameters of the MG model. The total operating cost has been discussed, focusing on the system's economic assessment—the COE, the NPC, and overall operation and maintenance (O&M) cost. Instead of considering the full capacity of each RESs, the sharing of each source as the parameter f_{ren} has also been discussed [38].

(1) Cost of Energy (COE): The per-unit COE consumed at the consumer end is the total energy cost. The mathematical expression has been mentioned in the following equation:

$$COE = \frac{C_{ann,tot} - C_{\text{boiler}} H_{\text{served}}}{E_{\text{served}}}. \tag{12}$$

(2) Net Present Cost (NPC): The total cost analysis of system components, operations, and the revenue collected gives the NPC of the designed MG. It includes the cost of operations, initial cost, and revenue collection for a given period. The mathematical expression has been mentioned in the following equation:

$$C_{NPC} = \sum_{n=i}^{n} \frac{CF_n}{(1+i)^n}. \tag{13}$$

CF represents the cash flow, i represents the discount rate, and n represents the time period.

(3) Renewable Fraction (f_{ren}): The quantity of power delivered to the load at the consumer end via different RESs

(in percentage) is a renewable fraction. In the system assessment process regarding renewable extraction and usage, f_{ren} is the critical parameter. The increase in f_{ren} leads to reduced emission and COE. The mathematical expression has been mentioned in the following equation:

$$f_{ren} = 1 - \frac{E_{\text{nonren}} + H_{\text{nonren}}}{E_{\text{served}} + H_{\text{served}}}. \tag{14}$$

(4) Operating Cost ($C_{\text{operating}}$): The cost analysis focuses on the component's analytical value, excluding its initial and installation cost. The mathematical expression of operating cost has been mentioned in the following equation:

$$C_{\text{operating}} = C_{ann,tot} - C_{ann,cap}. \tag{15}$$

(5) Operation and Maintenance costs (O&M): It is the total sum of the cost involved in the operation and maintenance of the system components. The other charges related to O&M include costs related to the penalties, etc. Below, the mathematical equation has been presented.

$$C_{om,\,other} = C_{om,\,fixed} + C_{cs} + C_{\text{emission}}. \tag{16}$$

2.4. System Configuration and Description

2.4.1. MATLAB–Simulink Model. Focusing on the technical grounds of MG feasibility, the electrical parameters identified in the literature include voltage, frequency, and power sharing [39, 40]. As per the IEEE standards and CERC Staff Paper March 2011, the feasible frequency range under the Indian Electricity Grid Code (IEGC) must be 49.5 Hz to 50.2 Hz and ±5% of the standard voltage [41, 42].

The proposed model of the residential MG is shown in Figure 3. The system includes a wind energy source (WES) of 25 kW capacity, a solar PV of 15 kW, and a lithium-ion-based battery energy storage system (BESS) with a rated capacity of 360 V and 55 Ah. The figure shows that the power sources are connected through the converter modules with the DC link. The conventional PID-based voltage regulator further controls and regulates the inverter output. The system is designed for the total peak electrical load of approximately 25 kW capacity, where 7.5 ± 2.5 kW is the critical load (CL), and the remaining is the noncritical load (NCL). Table 7 presents the data employed to develop the simulation model using the MATLAB–Simulink software, version 2019b. The tabulated data represent the information related to the simulated system, system design, and fuzzy logic controller design.

2.4.2. HOMER Pro Model. The developed system incorporates power sources, including a solar PV module, a wind energy module, and a battery energy storage system. Designing such a system combines two or more renewable sources to improve operating characteristics, reliability, and performance. The sources are connected using the converter module, as shown in Figure 4, whereas the related data are tabulated in Tables 3–6.

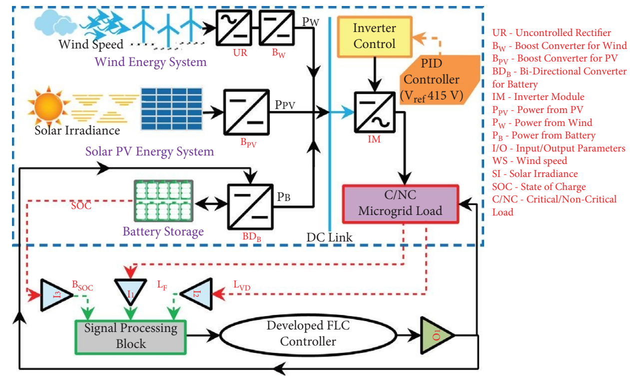


Figure 3: MG model under investigation.

Table 7: Tabulated data for the simulation model.

Parameter	Value
Simulation mode	Normal
Start and stop time	0–4 sec.
Nominal P–P voltage (Vrms)	415 V
Nominal frequency	50 Hz
Sample time (s)	Ts (2 *e* − 6)
Number of block and components	240/1245
Max/Min step	Auto/Auto
Solver/Solver mode	ode23tb/Auto
Solver type	Variable step
Relative tolerance	1 *e* − 3
Consecutive ZCs step relative tolerance	10*128*eps
Max consecutive ZCs	1000
Base wind speed	7.2 m/s
Pitch angle	0°
PV rating	15 kW
Wind rating	25 kW
Battery rating	360 V/55 Ah
Solar STC	1000 W/m^2
Load value`	25 kW
FLC	Struct
Type	Mamdani
And/Or method	MinMax
Defuzz method	Centroid
Imp method	Min
Agg method	Max
Input (s)/Output (s)	3/1
Rule (s)	75
Tip ratio (optimal)	8.152

The two types of electric loads are also presented in the block diagram with their rated power consumption details. The model has been designed per the available geographical and load data, technical component details, and overall system cost. The HOMER Pro software is used in the present research to simulate the developed system. The software performs the energy balance analysis for a given period of a year and the calculation of each component's energy flows. Besides, it allows analyzing the system performance in different configurations between the given power sources. The HOMER Pro software provides the tabulated data of the optimal source configuration, COE, system NPC, system operation cost, O&M Cost, capital cost, fuel consumption, etc.

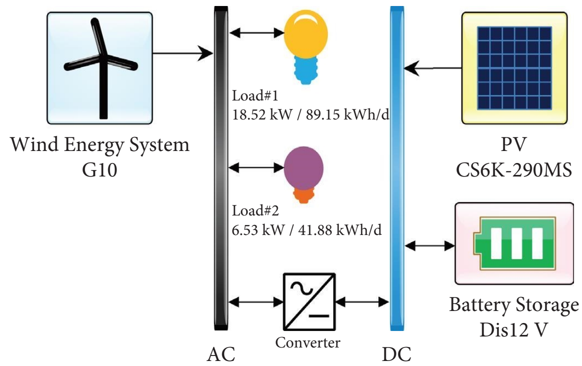


Figure 4: MG layout in HOMER Pro software.

2.4.3. Hardware Test Bench Setup. Converging from the techno-economic assessment toward the ideology of real-time implementation assessment of the developed system, the prototype of the hardware test bench is shown in Figure 5.

The figure conceptualizes the MG model as shown in Figure 3. The input to the test bench prototype is given through analog channels, and the percentage of load met is analyzed in the output section. The essential purpose of the developed setup is to analyze the performance of PLC for the real-time implementation of the system along with EMS control algorithm validation. The CCW software embedded all the possible practical conditions in the Rockwell-Allen Bradley Automation Product–Micro820 PLC controller [43]. Table 8 presents the information related to the developed hardware setup, where several components have been employed. The tabulated data represent the information related to each component shown in Figure 5, including the power supply, software used, total input/output channels, and programming language.

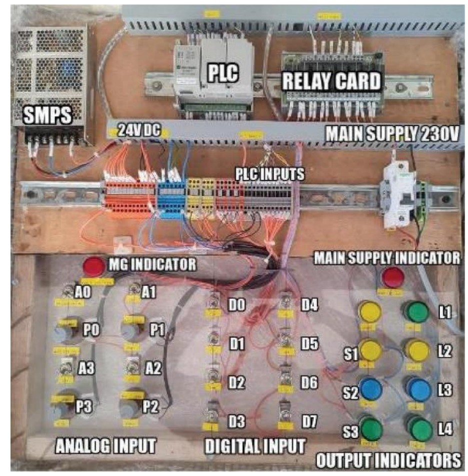


Figure 5: PLC-based control test bench.

2.5. Working Flowchart for Proposed Methodology. This section presents the functional and comprehensive flowchart of the proposed methodology while aiming at the complete assessment of the developed MG. The flowchart illustrates the different aspects of assessment done in this work to validate the proposed MG structure's novel performance. Besides, the step-by-step details of the flowchart shown in Figure 6 have also been organized. In Figure 6, the comprehensive layout of the proposed methodology has been presented.

The flowchart can be explained in 3 steps, as discussed as follows:

(i) Step 1—Technical Assessment: Considering the aspects of technical assessment of the developed MG, the MATLAB–Simulink platform has been employed. The variable and uncertain renewable output as the critical condition has been considered to validate the system performance. Significant parameters, including the system voltage, frequency, accuracy in power sharing, and the DC-link voltage, have been considered for the analysis. For this purpose, the different standards and regulations passed by the Electricity Board of India have been considered to validate the system's feasibility. It is noteworthy that such case studies must be simulated before the practical realization of the existing system. This way, through simulations, the technical assessment can be analyzed.

(ii) Step 2—Economic Assessment: Considering the given configuration, it is crucial to assess the economic aspects of the MG. The present research focuses on the key parameters such as COE, O&M Cost. The other important part of such analysis is the set constraints, including the minimized unmet load percentage, maximum renewable extraction, and minimum carbon emissions. Thus, employing the HOMER Pro software, the economic analysis of the developed system can be done for several resource combinations, out of which the most feasible and optimized solution can be attained.

(iii) Step 3—Implementation Assessment: The final stage of the MG assessment is based on its implementation while focusing on the operation and control aspects. For this purpose, the present state of art research includes the programmable logic controller (PLC) based hardware test bench for assessment purposes. The hardware test bench (shown in Figure 5) is developed using the Rockwell–Allen Bradley–Micro820 PLC. The developed hardware test bench can practically showcase the ideology of energy management and load curtailment for the developed MG under experimental conditions. For instance, only the critical load must be satisfied in low renewable output, and some load curtailment must be done. This way, the implementation assessment can be done to authorize the complete feasibility analysis of the developed MG.

3. Results and Discussion

3.1. Technical Simulation Results. Following Figures 3 and 6, the simulation results for developed MG using MATLAB–Simulink software are presented in Figures 7(a)–7(d).

Table 8: Salient features and summarized details of the hardware system.

Sr. No.	Feature	Details
1.	Power supply	230 V AC
2.	SMPS	230 V AC to 24 V DC
3.	PLC	Reconfigurable 12/8 I/O 24 V DC
3.1.	Product name/Catalog ID	Micro820/2080-LC20-20QBB
3.2.	Software used	CCW standard edition v12.0
3.3.	Total input/output	12/8 (analog I/O channels–4/1 and digital I/O channels–8/7)
3.4.	Dimensions (H × W × D, mm)	90 × 100 × 80
3.5.	User-defined function blocks	Yes
3.6.	Languages	Ladder diagram, function block, structured text
3.7.	Program steps	10,000 steps
3.8.	MicroSD card slot	1 (32 GB max.)
3.9.	Base serial port	RS232/485 nonisolated, CIP serial, modbus RTU, ASCII
3.10.	Base programming port	Embedded ethernet port
3.11.	Reconfigurable	Yes
4.	Relay card	24 V DC 8channel card with the indicator (s)
5.	LED lights	Pilot LEDs with 22.5 mm diameter
6.	Potentiometer	5 kΩ with knob 0–180̊
7.	Toggle switches	6 A on/off metallic switches

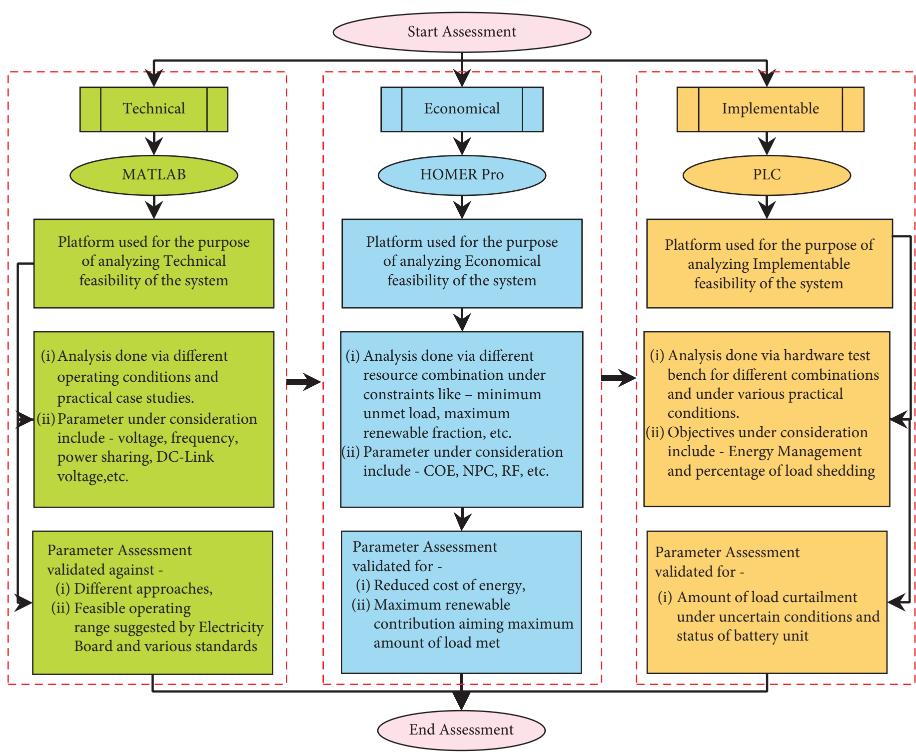


Figure 6: The layout of the proposed methodology.

The aforementioned key parameters, i.e., voltage, frequency, and power sharing, have been showcased under the ideal and nonideal scenarios.

Figure 7(a) presents the system RMS voltage under ideal conditions (415 V). Figure 7(b) presents the system frequency observed across the connected load. Figure 7(d) presents the power sharing among renewable sources while fulfilling the total load demand. It is worth analyzing that the frequency and voltage parameters lie in the feasible range of operation, i.e., the permissible range (49.5 Hz to 50.2 Hz) as per Indian Electricity Grid Code (IEGC), and the obtained value shown in Figure 7(b) is minimum 49.97 Hz and maximum 50.05 Hz [41, 42]. Besides, the battery associated with the developed MG can be observed to be in the charging mode of operation considering the ideal conditions and sufficient renewable output, as shown in Figure 7(c). Disparate to the ideal conditions, the MG feasibility and operation have also been analyzed under nonideal conditions. Considering the small village load and islanded MG condition in remote regions, the drop in renewable output has been seen as one of the significant concerns in MG stability [40]. Henceforth, a similar condition has been

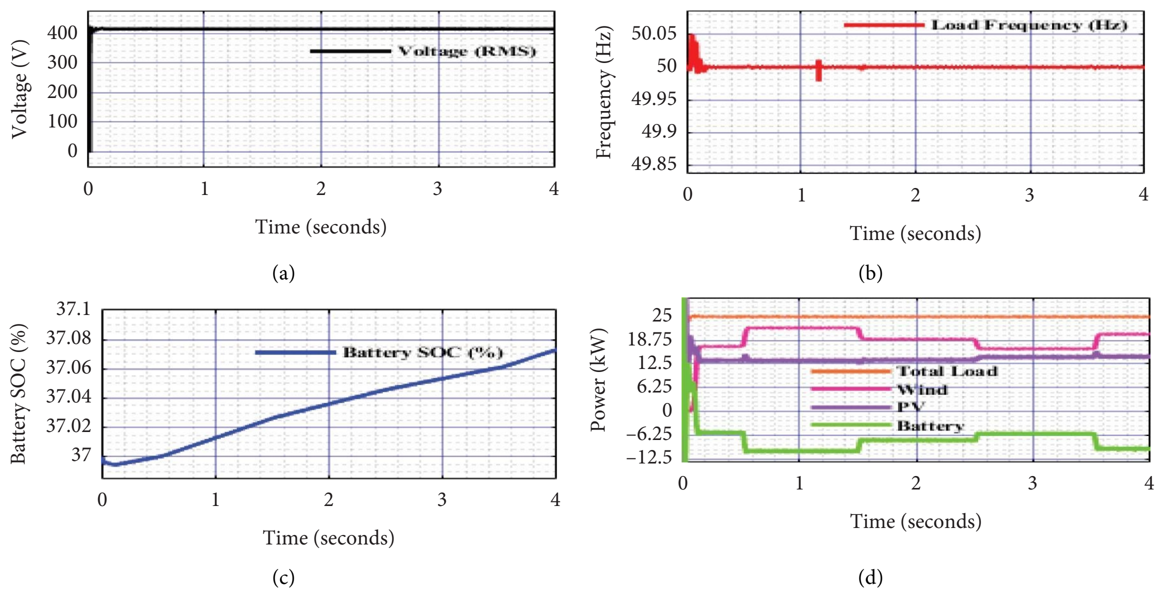


FIGURE 7: Technical feasibility analysis results—ideal conditions. (a). MG voltage parameter. (b). MG frequency parameter. (c). Battery SOC. (d). MG power sharing.

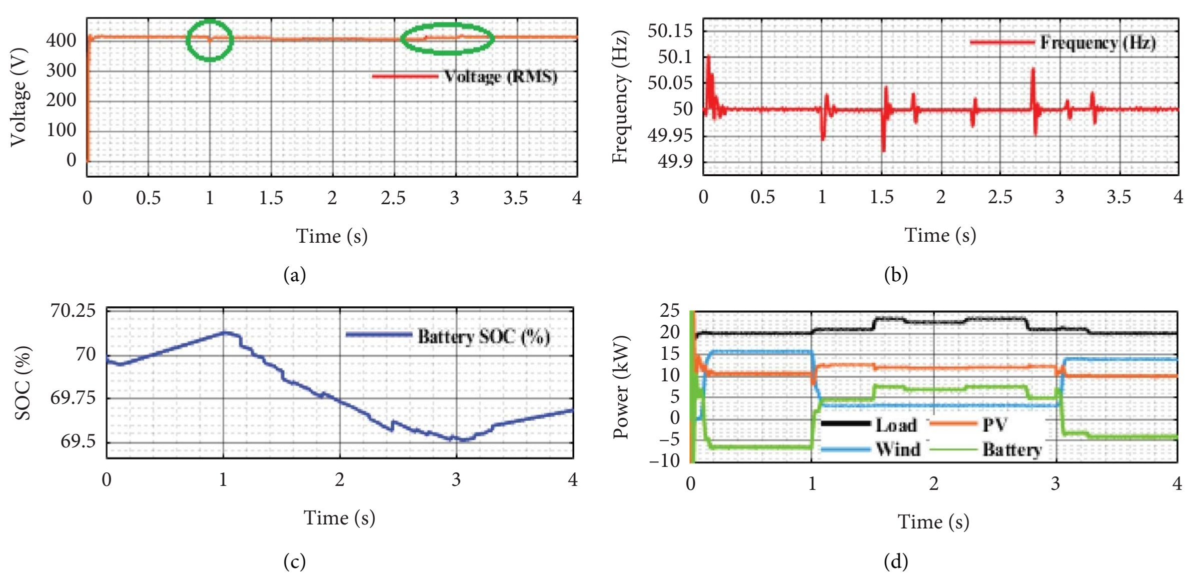


FIGURE 8: Technical feasibility analysis results—nonideal conditions. (a) MG voltage parameter. (b) MG frequency parameter. (c) BatterySOC. (d). MG power sharing.

simulated in this work for the feasibility and response analysis of the proposed MG.

In Figure 8, the fluctuation due to small perturbations in the simulation can be observed where the renewable output is supposed to drop. Figures 8(a) and 8(b) show that the voltage and frequency parameter deviation can be observed during this period. In the presence of a developed FLC controller, this fluctuation is balanced and strained within the permissible limits, i.e., 49.5 Hz to 50.2 Hz as per the Indian Electricity Grid Code (IEGC), and the obtained value shown in Figure 8(b) is the minimum 49.935 Hz and maximum 50.1 Hz [41, 42]. From Figure 8(c), the battery SOC can be observed to be in discharging mode once the renewable output drops due to the small perturbations. Notably, under small perturbations, the battery with a high SOC can feed the village's critical and noncritical load for a given period, after which load shedding according to load priority shall be performed. However, in the presence of large perturbations caused by a significant drop in solar and wind energy, the battery will discharge significantly. Henceforth, the considerable role of providing the ancillary support to the islanded system is well suited and taken by the battery ESS, as shown in Figure 8(d). The mathematical constraints and limitations are assumed per equations (7)–(10).

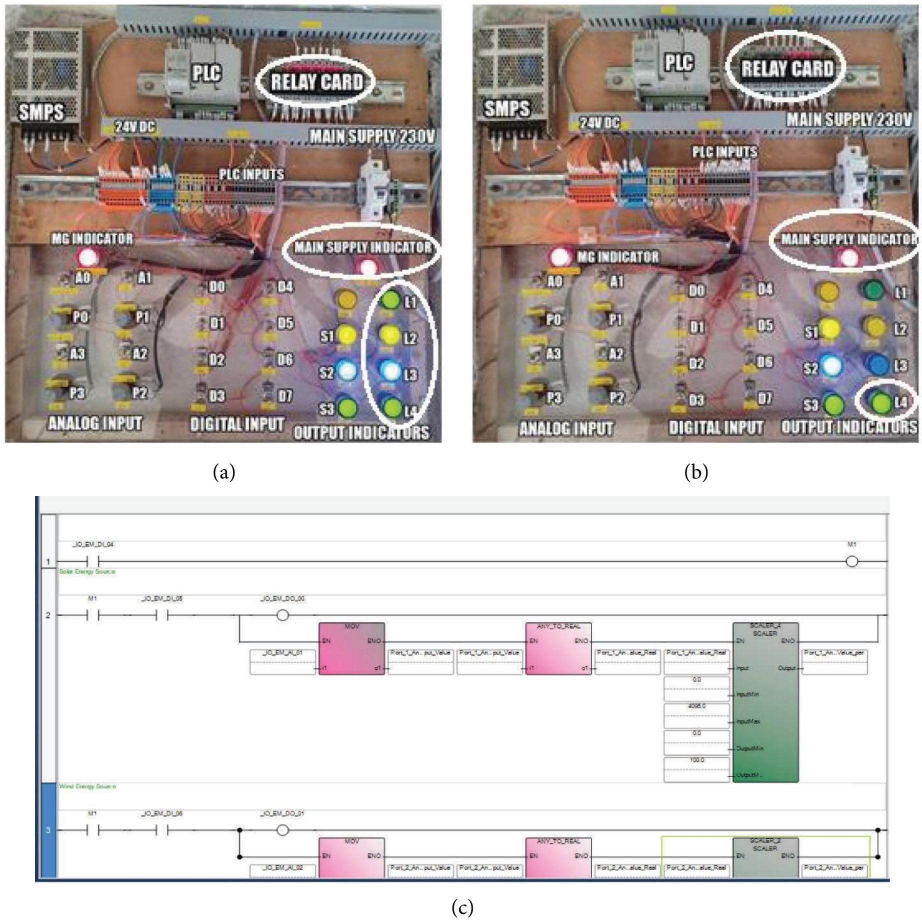


Figure 9: Implementation assessment results. (a) Ideal conditions: L1, L2, L3, and L4 are ON indicating 100% load fulfillment. (b) Nonideal conditions: L4 is ON, indicating only 25% load fulfillment. (c) PLC ladder logic window.

3.2. Economic Assessment Results. For an economic assessment of the proposed MG architecture for the Kibber region, Himachal Pradesh, the HOMER Pro software has been used in this research. As discussed, the software allows the optimal combination of resources for the said location from a techno-economic viewpoint. In addition, a separate sensitivity analysis has been performed to analyze the system response regarding the change in average values of RESs. The comprehensive details and results for the developed MG for the most feasible combinations have been tabulated in Table 9. Notably, the cost for various components and parameters has been considered in US Dollars ($), which in Indian Rupee (INR) is equal to Rs. 75/- approximately $1 as of January 25, 2022 [44].

The analysis shows that the best configuration suitable for the given location is the PV + battery combination with the COE of $0.127. This configuration is followed by the PV + wind + battery combination with COE as $0.171. This increase in COE value is due to the high operating cost, O&M cost, etc., which are higher in the other two cases. However, with the high COE and other cost parameters, the wind + battery combination stands last as the most feasible solution. The other observations made from the analysis include the following:

(i) Negligible or deficient unmet load percentage with the value of 0.021020%, $2.20E-15\%$, and 0.057023%, respectively, along with 100% f_{ren}. It validates the maximum renewable extraction for the minimum unmet load percentage.

(ii) Islanded MG system that eliminates the CO_2 emissions from the concerned site.

(iii) Without any generator set, the system's fuel consumption is nonexistent, which validates minimum environmental damage.

(iv) In the case of future developments concerning net metering, the scope of excess electricity that can be supplied back to the grid or utilized for other purposes is high. For each case, the excess electricity percentage varies from 36.56232%, 39.48045%, and 66.7873%, respectively.

(v) PV and battery combination is a viable option given the COE, system operating cost, and O&M costs. Furthermore, in this combination, the PV unit can supply the electric load for most hours, covering the peak load with the battery acting as ancillary support during the off hours. However, with significantly less difference in the COE, the other

Table 9: Comparison of the different optimized configurations.

Sr. No.	Classification	Parameter	Configuration		
			PV + battery	PV + wind + battery	Wind + battery
1.		Architecture/CS6K-290MS (kW)	54	47.25	—
2.		Architecture/G10	0	1	13
3.	Architecture	Architecture/Dis12 V	183	177	213
4.		Architecture/Converter (kW)	25.729	26.916	24.657
5.		Architecture/Dispatch	CC	CC	CC
6.		Cost/COE ($)	0.127	0.171	0.277
7.		Cost/NPC ($)	248966.1	282958.1	818979.3
8.		Cost/Operating cost ($/yr)	3749.477	4148.756	10867.12
9.		Cost/Initial capital ($)	20049.6	229325	678494.4
10.	Cost	Cost/Fuel cost ($/yr)	0	0	0
11.		Cost/o&M ($/yr)	2952.503	3123.583	6814.287
12.		CS6K-290MS/Capital cost ($)	111857.1	97875	—
13.		G10/Capital cost ($)	—	44500	578500
14.		G10/o&M cost ($)	—	400	5200
15.		System/Ren frac (%)	100	100	100
16.		System/Total fuel (L/yr)	0	0	0
17.		System/Cap short (%)	0.09759784	0.000764332	0.0985902
18.		System/Excess elec (%)	36.56232	39.48045	66.7873
19.		System/Unmet load (%)	0.02102028	2.20E-15	0.05702304
20.		System/Unmet load (kWh/yr)	12.37111	1.29E-12	33.55989
21.	System component (s)	System/CO_2 (kg/yr)	0	0	0
22.		CS6K-290MS/Production (kWh/yr)	104196.7	91172.15	—
23.		G10/Production (kWh/yr)	—	15099.26	196290.4
24.		Dis12 V/Autonomy (hr)	67.86707	65.64193	78.99283
25.		Dis12 V/Annual throughput (kWh/yr)	19737.41	13697.71	19485.57
26.		Dis12 V/Nominal capacity (kWh)	569.9479	551.2612	663.3821
27.		Dis12 V/Useable nominal capacity (kWh)	455.9584	441.0089	530.7056

combination of (PV + wind + battery) can also be preferred bearing in mind the renewable uncertainty.

Besides the above observations, the sensitivity analysis has been performed to understand the system's behavior considering key input parameters. These parameters include load fluctuation, uncertainty in solar radiation, and wind speed database. The observations are listed as follows:

(i) As the domestic load is considered dynamic, thus, a variation in load has been considered. It is worth noting that with the increase in the total load demand, more PV modules must be installed. It leads to an approximate rise of 14.5% in NPC. This increase in the number of PV modules analytically leads to a slight decrease in the COE from $0.127 to $0.123.

(ii) The average solar radiation database varies from 4.50 kWh/m^2/day to 5.50 kWh/m^2/day, keeping other parameters fixed. Remarkably, with the increase in solar radiation, the PV power output increases and thus leads to a drop in COE from $0.127 to $0.124. However, the COE increases to $0.130 when the solar radiation is dropped down to a 4.5 kWh/m^2/day value.

(iii) Likewise, to solar radiation, the wind speed data are varied in the range of 6.5 m/s to 7.5 m/s value. It has been observed that the number of wind units remains the same while varying the wind speed, though the COE varies significantly. For an increase in wind speed, the COE for the most feasible case drops from $0.171 to $0.164. Simultaneously, it increases to $0.175 for the drop in wind speed. Notably, the NPC also varies with the variation in RESs data.

(iv) Lastly, with the variation in the capital cost of ESS, the COE and other cost parameters vary significantly. When the capital cost of the battery is reduced from $400 to $350, the NPC of the system drops by 10–15% and COE drops to a minimum value of $0.111. However, if the capital cost is increased to $450, a considerable increase in the COE and NPC has been observed. Thus, a drop in ESS price leads to a more economical and feasible MG architecture.

3.3. Implementation—PLC Hardware Test Bench Results. The hardware test bench results have been presented in Figure 9. As per Figure 9(a), the demonstration of the test bench using a PLC controller can be analyzed under ideal conditions where no perturbations are observed. It is evident that with maximum renewable output, the controller indicates fulfilling all the connected electrical load demands (100% load fulfillment). In the present case, it can be observed that the relay channel output is full for ideal conditions, i.e., a high signal is given to all the connected load points. However, in the case of nonideal conditions, i.e., a system with perturbations given a drop in renewable output, the controller drops the weightage of the load demand to 25% of the total load, which is the critical load, as shown in Figure 9(b). Notably, such a case is tested with low battery SOC. Furthermore, in nonideal conditions, the relay channel output is partially high, indicating that fewer connected loads must be turned on. However, in actual scenarios, the relay channel output is given to the residential MCBs (miniature circuit breakers) to switch on/off the CL/NCL. It is done to balance the load curtailment/demand-side management strategy appropriately. Furthermore, Figure 9(c) demonstrates the programming window of the PLC controller software where the ladder logic for Rockwell-Allen Bradley Automation Product–Micro820 has been developed.

Thus, such implementation ensures that the proposed MG for the remote region of Kibber village can be implemented using the robust PLC controller as the chief unit of control and operations.

3.4. Recommendations. As per the Indian status of rural and remote electrification, a few recommendations have been proposed focusing on the subsequent stage development in the existing policies and are mentioned as follows:

(i) In general, the existing renowned policies for rural electrification include Pradhan Mantri Gramodaya Yojna (PMGY), Kutir Jyoti Program (KJP), Minimum Needs Program (MNP), Accelerated Rural Electrification Program (AREP), Rural Electricity Supply Technology Mission (REST), Rajiv Gandhi Grameen Vidyutikaran Yojna. However, these policies mainly focus on the availability of electricity in the rural region. But, with the recent development in renewable technology, the authors recommend moving towards the next development objective: reliability. Remarkably, the objective should be to provide more reliable and continuous electricity to such areas. Besides, it can be well accompanied by maximum renewable extraction as another critical objective.

(ii) The authors recommend implementing the new policies based on MGs' power quality and stability index, giving users a more secure and reliable electrical connection.

(iii) Besides technological developments, the authors recommend subsidizing or reducing the cost of BESS and other high-cost MG equipment to boost electricity affordability for such regions. Besides this, more usage of renewable technology in the given areas should be encouraged to increase electricity's affordability and hence needs special attention.

(iv) Lastly, a complete assessment of the proposed MG must be done before its deployment to achieve the above objectives, along with enhanced security, stable operation, and control aspects. This assessment includes technical simulations, economic analysis, and controller testing.

4. Conclusions

With the recent advancement in renewable energy technology and national policies, the increasing energy demand can be easily fulfilled, especially for remote and rural locations. Exclusively, solar and wind energy resources are abundant considering the state of Himachal Pradesh in the Northern region of India. Thus, aiming at reliable rural electrification, this study presented the planning and assessment of the islanded MG for the Kibber region. The comprehensive system assessment incorporated its three aspects, i.e., technical, economic, and implementation. The technical analysis has been performed using the MATLAB–Simulink platform to investigate the power sharing and response of the developed MG under uncertain conditions. The analysis shows that the system simulation performs significantly well with the key electrical parameters, including frequency, voltage, in a feasible operating range.

Following this, the economic analysis was performed to adjudicate the optimal number of generating units required, COE, and NPC, while considering the minimum unmet load percentage and maximum renewable contribution. The result analysis revealed the accuracy and performance of the developed system in satisfying the given load of the village while employing the HOMER Pro software. Besides, as per the investigation, it was also observed that the optimum sizing of the power converter units used in the system design minimizes the initial investment with minimum loss of renewable energy. Lastly, the PLC-based test bench was developed to validate the EMS control algorithm and to perform the implementation assessment. It was done while aiming at the stable operation and control of the developed system considering the real-time scenarios. This hardware prototype used the Allen-Bradley PLC with ladder logic to perform real-time case studies, including sudden renewable output changes, low battery status, and dependent decision-making. It was observed that with the drop in renewable output, the controller performed the load curtailment as per the load priority aiming for stable MG operation. Thus, a reconfigurable PLC can be the most robust controller in such harsh conditions for optimal control of the developed system.

Henceforth, it can be concluded that a particular MG configuration may not be feasible for all geographical locations, and thus, a complete assessment is of utmost importance. Therefore, this paper provides guidelines and a systematic approach for assessing the proposed system. This process will significantly allow the researchers to plan and perform a comprehensive assessment for MGs that can be developed in rural and remote locations.

In future studies, the authors plan to visit Kibber village or likewise location to view the actual situation and cost-related parameters, such as insurance for solar panels, battery damage data, which will allow for a better and more accurate assessment of similar locations. Furthermore, a multidimensional approach with a more diversified electrical load and alternatives for battery storage is also a part of the future scope of this present study.

List of symbols and abbreviations:

MG: Microgrid
RESs: Renewable energy sources
ESS: Energy storage system
COE: Cost of energy
INR: Indian national rupee
HOMER: Hybrid optimization model for multiple energy resources
SOC: State of charge
STC: Standard test condition
NASA: National aeronautics and space administration
NPC: Net present cost
NREL: National renewable energy lab
O&M: Operating & maintenance
PV: Photovoltaic
SOC_{Min}: Minimum limits of SOC
$C_{ann,tot}$: Total annualized cost of the system
C_{boiler}: Boiler marginal cost
H_{served}: Total thermal load served
E_{served}: Total electric load served
C_{F0}: Initial capital cost
N: Projected lifetime for system
i: Annual rate of interest
C_{Ft}: Amount of cash flow in the given total number of "t" years
f_{ren}: Renewable fraction
E_{nonren}: Nonrenewable electrical energy production
$E_{grid,sales}$: Total energy sold to the main grid
H_{nonren}: Nonrenewable thermal energy production
E_{served}: Total electrical load served in the grid
H_{served}: Total thermal load served
$C_{\text{operating}}$: Operating cost
$C_{\text{ann,cap}}$: Total annualized capital cost
$C_{\text{om, other}}$: Other operation and maintenance cost
$C_{\text{om,fixed}}$: System fixed O&M cost
C_{cs}: Penalty for capacity shortage
$C_{emissions}$: Penalty for emissions
P_{PV}: Power of PV module
Y_{PV}: Rated capacity of PV module
f_{PV}: Derating factor of PV module
$\overline{G}_T$: Incident solar irradiance
$\overline{G}_{T,STC}$: Solar irradiance at standard test conditions
T_C: Cell temperature
$T_{C,STC}$: Cell temperature under standard test conditions
α_p: Temperature coefficient
$\eta_{mp,STC}$: Maximum power point efficiency at standard test conditions
τ: Solar transmittance
a: Solar absorptance
P_{WT}: Mechanical power of wind turbine
P_{rated}: Rated power of wind turbine
V_R: Rated speed of wind turbine
V_{C0}: Cut-off speed of wind turbine
V_{C1}: Cut-in speed of wind turbine
ρ: Air density
x: Power-law exponent
R: Radius of a turbine blade
P_W: Wind generator output power
C_P: Power coefficient
λ: Tip speed ratio
β: Blade pitch angle
V: Wind speed
H_i: Reference height
V_i: Wind speed at the reference height H_i
η: Generator efficiency
A_W: Total swept area
P_A: Actual power of the wind turbine
$P_{\text{batt}}^{\text{Max}}$: Maximum storage capacity of battery
N_{batt}: Total number of batteries
V_{batt}: Voltage rating of battery
I_{batt}: Charging current rating of battery
n: Current position of battery SOC
$(n-1)$: Previous position of battery SOC
ΔSOC: Variation in SOC
DOD: Depth of discharge
P_L^M: Peak demand
η_{INV}: Efficiency of the inverter
RMS: Root mean square
DSM: Demand side management
CL: Critical load
NCL: Non-critical load
ANN: Artificial neural network
LM: Levenberg-Marquardt
MCB: Miniature circuit breaker

Data Availability

The data used to support the findings of this study are available from the corresponding author upon request.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

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