Opportunities and Challenges in Sustainability
https://www.acadlore.com/journals/OCS

Cost-Effective Optimization of Hybrid Renewable Energy System for Micro, Small, and Medium Enterprises: A Decision-Making Framework Integrating MEREC and MARCOS

Khushi Sehgal[1], Harsimran Kaur[1], Swapandeep Kaur[1*], Sehijpal Singh[2,3], Harpreet Kaur Channi[1], Željko Stević[4]

[1] Department of Electrical Engineering, Guru Nanak Dev Engineering College, 141006 Ludhiana, India
[2] Department of Mechanical and Production Engineering, Guru Nanak Dev Engineering College, 141006 Ludhiana, India
[3] Department of Mechanical Engineering, Graphic Era (Deemed to be University), 248002 Dehradun, India
[4] Faculty of Transport and Traffic Engineering, University of East Sarajevo, 74000 Doboj, Bosnia and Herzegovina

[*] Correspondence: Swapandeep Kaur (swapandeep80@gmail.com)

Received: 01-03-2025 **Revised:** 02-27-2025 **Accepted:** 03-05-2025

Citation: Sehgal, K., Kaur, H., Kaur, S., Singh, S., Channi, H. K., & Stević, Z. (2025). Cost-effective optimization of hybrid renewable energy system for micro, small, and medium enterprises: A decision-making framework integrating MEREC and MARCOS. *Oppor Chall. Sustain.*, *4*(1), 17-32. https://doi.org/10.56578/ocs040102.

Abstract: The transition to renewable energy sources (RES) for electricity generation has gained significant momentum due to environmental and sustainability concerns. However, the high initial costs associated with RES implementation remain a critical barrier, particularly for micro, small, and medium enterprises (MSMEs). To address this challenge, a cost-effective optimization framework for the hybrid renewable energy system (HRES) was proposed, integrating advanced decision-making methodologies. The study focused on a case study of an MSME in a rural village in Ludhiana, Punjab, where the feasibility of various HRES configurations was evaluated using HOMER Pro software. The optimization process aims to minimize key financial metrics, including net present cost (NPC), operation and maintenance (O&M) costs, and the levelized cost of energy (LCOE), while simultaneously reducing carbon emissions. Sensitivity analyses were conducted to assess the impact of critical parameters such as diesel prices, inflation rates, and system constraints. To rank the HRES configurations, a multi-criteria decision-making (MCDM) approach is employed, combining the Method based on the Removal Effects of Criteria (MEREC) for weight determination and the Measurement of Alternatives and Ranking according to Compromise Solution (MARCOS) for system ranking. The results demonstrate that the proposed framework effectively identifies the most cost-effective and environmentally sustainable HRES configuration, providing a robust decision-making tool for MSMEs. This study not only contributes to the growing body of knowledge on RES optimization but also offers practical insights for policymakers and stakeholders aiming to promote renewable energy adoption in small-scale industrial settings.

Keywords: Hybrid renewable energy system (HRES); optimization; HOMER Pro; Measurement of Alternatives and Ranking according to Compromise Solution (MARCOS); Multi-criteria decision-making (MCDM)

1. Introduction

Punjab has suitable biomass and solar energy generation potential. The total contribution of RES, mainly biomass and solar, is about 6-7% of the total energy generation. Punjab has a rich agricultural heritage; thus, this agricultural residue can act as a significant raw material for biomass that can be further used for energy generation. Biomass energy generation via agricultural waste (mainly consisting of wheat and paddy) and animal waste (mainly consisting of cows and buffaloes) is up to 105 MWh and 124 GWh. The main crops contributing to energy generation are wheat, paddy, maize, sugarcane, potatoes, and cauliflower, where the wheat and paddy residue collectively provide approximately 90 GWh generation (Channi et al., 2022). The potential of biomass energy for agricultural and livestock material is highest in the Ferozepur District, followed by Sangrur and Ludhiana, with the least potential in the Mohali and Rupnagar Districts. Thus, using biomass energy resources has saved millions of tonnes of coal, thus saving fuel costs and emissions (Mittal et al., 2019). Punjab contributes 18% of biomass energy generation to the total energy production in India, and the state can produce about 3170 MW of power from biomass resources. The primary resources of methane generation are dairy manure, poultry manure, wheat, and rice straw. Biogas generated via anaerobic digestion has a maximum amount of methane, carbon dioxide, and carbon monoxide (Kumar et al., 2024a). Biogas, having a methane content of approximately 60%, can generate up to 6 kWh per cubic meter under normal conditions. Punjab significantly contributes to biomass due to more agricultural production (e.g., rice stalks, wheat stalks, bagasse, etc.), human waste, and dairy waste (e.g., cow dung) with the Hydraulic Retention Time (HRT) of a biogas plant for up to 40 days. The total number of livestock is 1354, and the total amount of waste produced in kg per day is 20310 for rural areas of the Mansa District of Punjab (Saha et al., 2023). The total crop residue available from rice, wheat, maize, and sugarcane is up to 29786 kilotons per year. The biomethane generation in Punjab is up to 1.5 billion m^3 up to 2020 (Singh et al., 2020a). The potential of renewable energy generation in Punjab is about 9-10%. Solar and biomass potential is about 3470 MW and 2800 MW, respectively, whereas small hydro and energy from waste is about 486 MW collectively. The scope of bioenergy is more from wheat crops, followed by sugarcane, pulses, and oilseeds (e.g., sunflower and mustard) (Hiloidhari et al., 2014).

The biomass potential of India is about 3-4% of the total energy generation from renewable energy generation and is expected to increase by 30% in the upcoming financial years till 2030 (Negi et al., 2023). The renewable potential in India is about 35-40% of the total generation. Punjab has aimed in 2022 to achieve energy generation of up to 4770 MW with an installed capacity of 1154 MW (Ghosh & Acharyya, 2023). Renewable energy generation in Punjab has harnessed up to 20-22% till the financial year 2022. Mansa District has a capacity of 31.5 MW, followed by Ludhiana, Patiala, Moga, Amritsar, and Bathinda. (Hooda et al., 2023). Renewable generation in Punjab is up to 712 MU till May 2024, where the generation from solar is 136 MU, from biomass is 56 MU, from bagasse is 20 MU, from small hydro is 73 MU, and from large hydro is 430MU till May 2024 (Debnath et al., 2021).

1.1 Related Work

Ahmad et al. (2018) analyzed cost factors for an HRES with photovoltaic (PV) and wind integrated with a biomass energy system for Kallar Kahar Village near Punjab, Pakistan. The system was simulated in HOMER Pro. Results were also analyzed according to sensitivity parameters. Al Garni et al. (2018) presented an optimal grid-connected PV system design for Makkah, Saudi Arabia, using HOMER. Simulation was done using different configurations of dual-axis tracking systems. The configurations with different tracking systems were analyzed in terms of cost, where the system with a vertical axis tracker was simulated as the best in terms of least NPC. Khan et al. (2018) presented a practical implementation of a grid-connected PV system using HOMER. A case study of the University of Kuala Lumpur, Malaysia, was considered. The system was simulated as the most optimized model in terms of costs by considering sensitivity parameters. Murugaperumal & Raj (2019) analyzed a hybrid system with solar, wind, and biomass energy resources for a rural Korkadu area near Pondicherry, India. The system was simulated using HOMER Pro, and the system, which had all the energy resources, was simulated as the most optimized one in terms of costs. The system load forecasting was done using MATLAB's artificial neural network technique.

Suresh & Kiranmayi (2020) conducted research on off-grid PV, wind, fuel cell, biogas, and biomass HRES for a rural village in Karnataka. Cost analysis was done for different combinations using HOMER Pro and the genetic algorithm in MATLAB. The system with all the resources was simulated as the most optimized model. Jahangir & Cheraghi (2020) analyzed the HRES with solar, wind, and biomass energy systems for a rural area in Iran. The system was analyzed for both on- and off-grid systems, and cost factors were compared. Sensitivity parameters like inflation rate were also considered. A system with a PV-biomass battery and converter was simulated as the most optimized model in terms of cost and emissions. The system was also compared in terms of emissions with the coal-based system. Chowdhury et al. (2020) analyzed PV-biomass energy systems technically and economically using RETScreen software for cost, emissions, and risk analysis. The case study was considered for a rural area in Ashuganj, Bangladesh. A system with both energy resources was simulated as the best model for all objective functions. Ullah et al. (2021) presented optimal planning for an on/off-grid HRES with solar, wind, hydro, and biomass for a rural area in Pakistan. The system was simulated using HOMER Pro. The system with grid-connected solar, hydro, and battery was simulated as the best optimal model as it resulted in the least costs and emissions. The different configurations formed were ranked as per the MCDM technique, which includes a hybrid technique with a fuzzy Analytic Hierarchy Process (AHP) technique, whose results were compared with the Technique of Order Preference by Similarity to Ideal Solution (TOPSIS) and Multi-Objective Optimization on the Basis of Ratio Analysis (MOORA) methods. Malik et al. (2020) analyzed an HRES with grid-connected PV, biomass, and wind systems for the western area of the Himalayan region. Different configurations of the system were simulated in HOMER Pro, and the grid-connected PV and biomass system was simulated as the best model for costing and emissions. The system was also analyzed with sensitivity parameters. Li et al. (2020) simulated HRES of off-grid PV-wind and biomass systems using HOMER for China's western region. The system was simulated as the most optimized model in terms of cost and emissions. Singh et al. (2020b) performed a cost analysis of PV integrated with a fuel cell system using HOMER and the ant bee colony-particle swarm optimization (ABC-PSO) method. The optimization results regarding LCOE were provided for ABC-PSO rather than HOMER Pro.

Al-Ghussain et al. (2021) presented a hybrid energy system with PV, wind, and biomass resources without storage for a university campus in the Middle East. The system was simulated using a generalized reduced algorithm to give optimal sizing of the components. The system's main objective was to compare the systems with and without storage systems. Yimen et al. (2021) simulated HRES having on/off-grid PV-biomass systems using HOMER Pro for a rural area in Cameroon. The system was analyzed using anaerobic digestion and gasification techniques for the biomass plant, and the system with a gasifier was simulated as the best one in terms of costs. Gupta et al. (2022) presented optimization for a renewable energy system with solar, biomass, and fuel cells as the primary energy resources for a rural village in India. The system was simulated in HOMER Pro for cost analysis using the hybrid chaotic PSO and slime mould algorithm, an enhanced PSO method. The system with all the energy resources was simulated as the most optimized model.

Ji et al. (2021) analyzed hybrid energy systems with solar, biomass, thermal sources, batteries, and diesel generator resources for the northern region of China. The system with all the resources was simulated as the most optimized model regarding costs for the region. Keshavarz-Ghorabaee et al. (2021) presented MEREC. The approach was used to assign weights to different values of options considered for ranking. The approach was compared regarding mean analysis for different options. Trung (2022) presented the MARCOS approach for ranking different applications for different loads. The method was compared to ranking methods like TOPSIS, VIKOR, MOORA, Proximity Indexed Value (PIV), Reference Ideal Method (RIM), etc. The applications considered were turning, milling, grinding, and ranking for different criteria. Seedahmed et al. (2022) optimized a grid-connected PV and battery storage system for a commercial area in Makkah, Saudi Arabia. The system was simulated as the most optimized model in terms of costs and emissions. Kumar & Channi (2022) simulated an HRES with PV and biomass as the main energy resources using HOMER Pro. A detailed analysis of costing and emissions was done for a rural area, Sidhwanbet in the Ludhiana District of Punjab. The different configurations of the system were compared in terms of costs and emissions, and the system with all the resources was simulated as the best. The ranking of the configuration was done using the TOPSIS method in order to get the most optimized model. Kumar et al. (2022) performed optimal sizing of off-grid systems having solar, biomass, battery, and diesel generators for remote areas in eastern India. The system was analyzed using HOMER Pro. The system having all the energy resources was simulated as the most optimized model by proving a 46% internal rate of return and a payback period of 2.04 years.

Dehshiri & Firoozabadi (2022) presented ranking of cities for solar projects implementation in Iran along with electrolyser optimization for hydrogen production. Stepwise weight assessment ratio analysis method for weighing the criteria and MARCOS method for ranking were the methods used. Economic analysis of the system was done using HOMER. Dinesh & Sawle (2022) performed optimization of grid-connected PV-wind system with a diesel generator for Ramanathapuram, Tail Nadu. The system was simulated as the most optimized model with an NPC of $13993 and an LCOE of $0.2. Ali et al. (2023) analyzed the performance of an HRES having wind, solar and biomass energy resources for Msallata City. The simulation was done using HOMER Pro. The ranking of the configurations was done using different multi-criteria decision analysis (MCDA) methods which ranked the system having wind and solar energy resources as the most optimized model. El-Araby (2023) presented the application of the MARCOS method for different industrial areas like robotics, forklift selection and material selection where different selection criteria or sensitivity parameters are involved. The comparison was done with TOPSIS, Preference Ranking Organization Method for Enrichment Evaluations (PROMETHEE) and VIKOR methods. As a result, the MARCOS method provided the most efficient results. Akpahou & Odoi-Yorke (2023) analyzed and performed a ranking of renewable energy systems having solar, wind, hydro, and biomass energy resources using CRITIC and entropy methods. As per the results, the system having solar was simulated as the most optimized model, followed by the system having wind and hydro energy resources. Kumar et al. (2024b) presented the importance and scope of rooftop solar energy plants for MSMEs in India. A hybrid model was presented, which had different weight-assigning techniques for different ranking techniques used. The MARCOS approach using weight assigning by the MEREC approach was considered the most optimized technique for ranking.

According to the literature review, research conducted in Punjab is limited. Therefore, this study aims to promote renewable energy not only in Punjab but also throughout the country and globally. Additionally, this study offers a comprehensive analysis of the system, covering cost and emission assessments as well as optimization plotting and ranking in one integrated approach, which is quite rare in the literature. In the current scenario, reducing electricity generation from non-RES is essential, as the depletion of fossil fuels and the pollution caused by their excessive use are major concerns. Consequently, effective cost analysis is crucial to encourage the adoption of solar and biogas energy. Systems with lower costs and emissions can help decrease dependence on non-RES. Furthermore, this study contributes to the development of solar and bioenergy in Ludhiana, Punjab, which may foster growth in the state’s energy sector. The need for this study is to analyze the HRES for effective practical implementation by achieving all the following objectives:

- To achieve a system with less NPC, LCOE, and O&M costs.
- To analyze the proposed system's emissions by observing the amount and type of greenhouse gas emissions released.
- To rank the systems according to the MARCOS technique and verify the most effective result to get the most optimized model.

This study significantly contributes to optimizing HRES for MSMEs through HOMER Pro (student version) and MARCOS. It emphasizes economic viability, environmental sustainability, and technical feasibility. By pinpointing cost-effective configurations that minimize NPC, LCOE, and emissions, the study advocates for cleaner energy solutions and less reliance on fossil fuels. It aids MSMEs by offering a scalable renewable energy model that guarantees cost savings and a consistent power supply, especially for rural industries. Moreover, the study improves decision-making via multi-criteria evaluation and sensitivity analysis, enabling adaptability to changing economic conditions. The results can assist policymakers in creating incentives for hybrid energy adoption, promoting sustainable development, and advancing India’s renewable energy objectives. Ultimately, this research presents a practical, data-informed strategy to speed up clean energy transitions, decrease carbon footprints, and enhance the role of decentralized renewable energy within industrial and rural areas.

2. Methodology

The HRES simulation was done using sensitivity parameters through the HOMER Pro software (Kaur et al., 2023; Kumar et al., 2024b).

2.1 Simulation Procedure in HOMER Pro

- Resources such as temperature and solar irradiation from the National Renewable Energy Laboratory (NREL) were initially downloaded for the selected location.
- The load was connected by taking into account its monthly unit consumption.
- All the equipment and energy resources were included based on their costs and sensitivity parameters (if any). Different control strategies were also considered, such as load following and cycle charging.
- Constraints or losses were also taken into account.
- The system was simulated, and various results were obtained for different configurations.
- The model with the lowest costs and emissions was the most optimized model.

2.1.1 Resources available

The annual scaled average solar global horizontal irradiance (GHI) is 5.82 kWh/m^2/day with an average of 19 kWh/m^2/day, the average clearness index is 2.2, and the annual average temperature is 31.5°C in June 2024. Average solar irradiation, clearness index, and temperature data are presented in Table 1 and represented via graphs in Figure 1.

Table 1. Monthly solar irradiation, clearness, and temperature data from NREL in HOMER Pro

Month	Average Temperature (°C)	Clearness Index	Irradiation (kWh/m^2/day)
JAN	12.89	0.595	3.43
FEB	16.05	0.604	4.25
MAR	22.26	0.6	5.23
APR	28.86	0.615	6.3
MAY	34.64	0.615	6.84
JUN	36.31	0.602	6.89
JULY	33.97	0.502	5.63
AUG	31.62	0.516	5.4
SEP	29.55	0.614	5.6
OCT	25.24	0.66	4.9
NOV	19.81	0.64	3.85
DEC	14.89	0.58	3.1
AVG	**25.51**	**0.595**	**5.12**

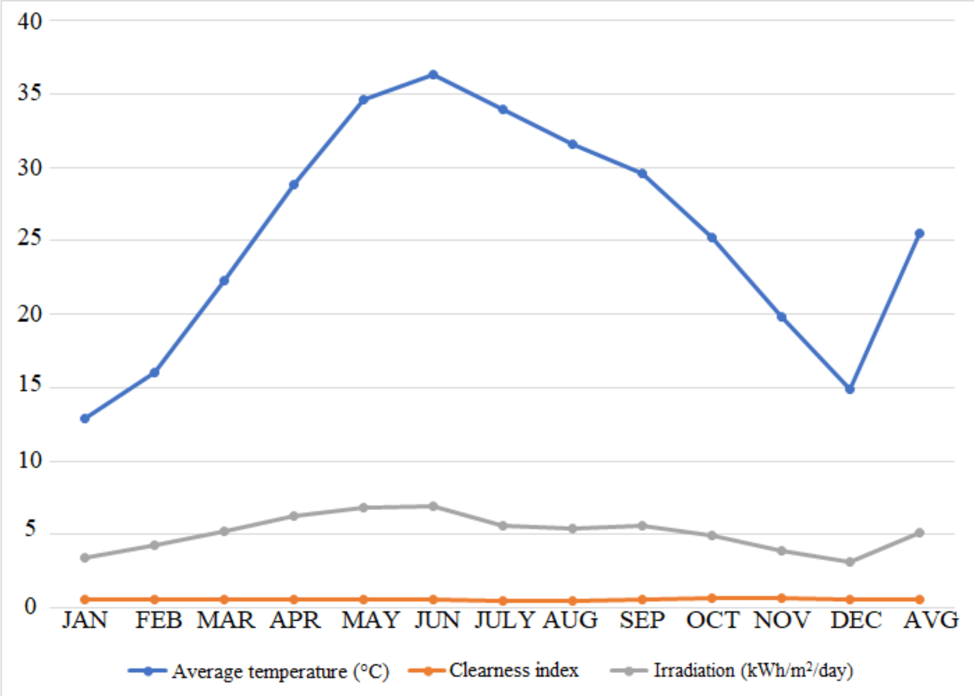

Figure 1. Variations of monthly average temperature (°C), clearness index, irradiation (kWh/m^2/day)

2.1.2 Load profile

The industrial load is a cluster of micro and small industries in the Ludhiana Village, which form a total load of approximately 650 kWh/day with a peak of 49.65 kW. Figure 2 represents the average unit consumption by the load.

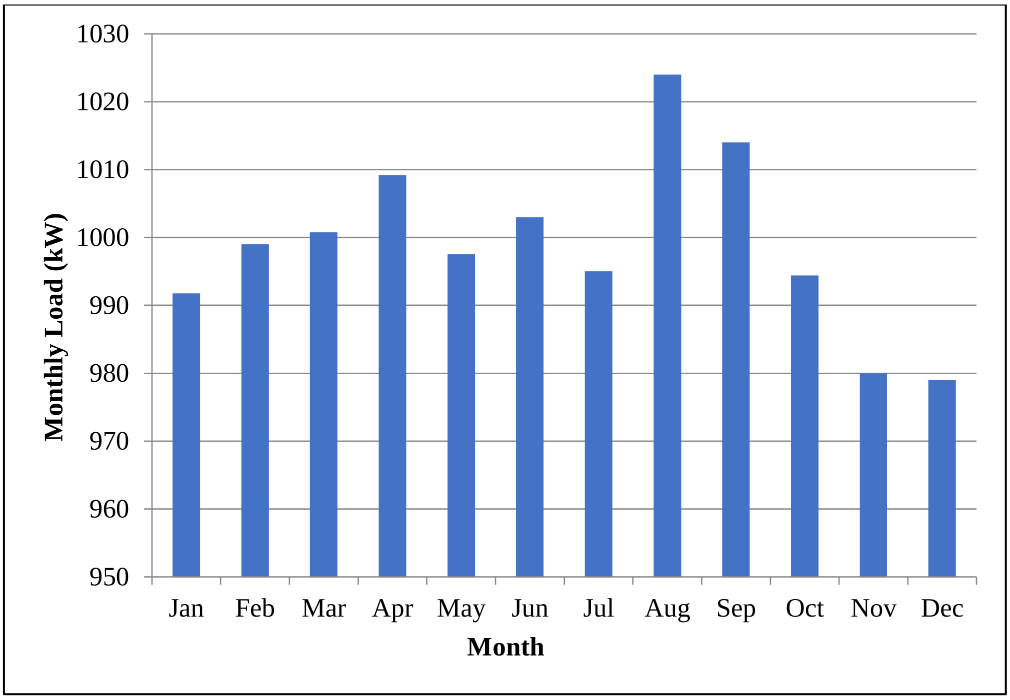

Figure 2. Average monthly load profile

2.1.3 Design and specifications of the system

- PV system: A generic type of solar panel rated at 150 kW (1 kW × 150 = 150 kW) with a de-rating factor of 80% and a lifespan of 25 years was used. The panel, made of monocrystalline silicon, was considered.
- Converter: A generic bidirectional 150 kW converter was considered. Its efficiency is assumed to be 95%.

• Biogas generator: A 400 kW biogas generator using dairy waste as fuel was considered. The average carbon content is 45, and the biogas's lower heating value is 5.5 MJ/kg. The gasification ratio is 0.7.

• Battery: In case of an outage, a generic lead-acid battery of 1 kWh each stores energy produced by the PV system, making for a total storage capacity of 100 kW. The charge state is 100%, with a minimum charge of 40%, and it is connected to a bidirectional converter.

Figure 3 shows a schematic diagram of the system. Table 2 shows a summary of the equipment details where all the main ratings and costs are represented.

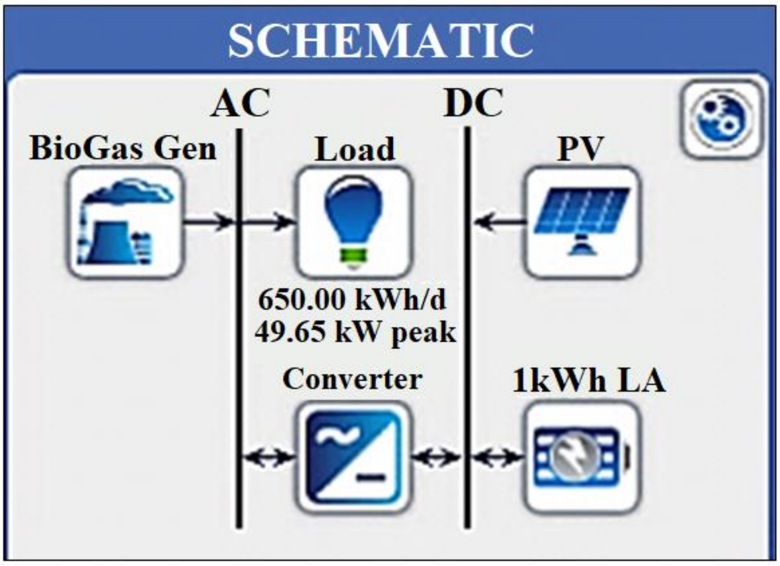

Figure 3. Schematic diagram of the system

Table 2. Specifications of the equipment

Component	Capacity	Type	Efficiency/Factor	Lifespan	Key Attributes	Cost (USD)
PV panels	150 kWp	Generic flat plate PV (1 kW), monocrystalline silicon	De-rating factor: 80%	25 years	High efficiency, long lifespan	65,853
Battery	100 kW	Generic 1 kWh lead-acid	State of charge: 100% (min: 40%)	Not specified	Backup storage for energy	450
Converter	150 kW	Generic bidirectional system converter	Efficiency: 95%	Not specified	Manages bidirectional power flow	500
Biogas generator	400 kW	Generic large genset (customized)	Gasification ratio: 0.7	Not specified	Uses dairy waste as fuel; LHV: 5.5 MJ/kg	1,50,000

2.1.4 Sensitivity parameters

Table 3 shows the sensitivity parameters used for simulating the most optimized model. These parameters will vary in the future, e.g., load variability, diesel rates, inflation rates, discount factor, etc. The project’s lifetime was taken as 25 years, with a return on investment of 5.2-4% and an internal rate of return of 7.5-8%. The inflation rate was taken as 2-8% and the discount factor as 8-16%.

Table 3. Sensitivity parameters

Sensitivity Parameter	Rate (%)
Inflation rate	2,5,8
Discount rate	8,12,16

The sensitivity parameters were considered for the most optimized model, and the results were displayed using optimization surface plots. The optimization plots were shown for all the equipment along the axes of battery versus converter and generator versus PV. Different colors represent the spectrums of various models involved and the contributions of other systems in the spectrum. The optimized values were marked with diamond-shaped coordinates, indicating the feasible result values obtained from HOMER Pro for that specific optimized model.

3. Ranking of the System Configurations by MARCOS and MEREC

The simulated configurations in HOMER Pro were ranked based on the results that satisfy the objective functions. As per the methodology presented (Dehshiri & Firoozabadi, 2022; El-Araby, 2023; Trung, 2022) for ranking the system, the approach considers different options that need to be satisfied and ranked as per different objective functions (criteria). The procedure of ranking is as follows:

Step 1: The decision matrix *D* of the options and criteria was represented according to the ideal (favorable) and anti-ideal (non-favorable) solutions as per Eq. (1):

$$D= \begin{matrix} & C_1 & C_2 & \dots & C_n \\ Anti\ ideal & a_1 & a_2 & \dots & a_n \\ O_1 & o_{11} & o_{12} & \dots & o_{1n} \\ O_2 & o_{21} & o_{22} & \dots & o_{2n} \\ \vdots & \dots & \dots & \dots & \dots \\ O_n & o_{n1} & o_{n2} & \dots & o_{nn} \\ Ideal & i_1 & i_2 & \dots & i_n \end{matrix} \quad (1)$$

Step 2: The decision matrix considers ideal (most favorable) and anti-ideal (less favorable) conditions, which were calculated as per Eq. (2) and Eq. (3), respectively.

$$\text{Ideal} = \begin{cases} \max_p o_{pq} & if\ q\epsilon F \\ \min_p o_{pq} & if\ q\epsilon CF \end{cases} \quad (2)$$

$$\text{Anti-ideal}= \begin{cases} \min_p o_{pq} & if\ q\epsilon F \\ \max_p o_{pq} & if\ q\epsilon CF \end{cases} \quad (3)$$

where, *F* represents the favorable value of the simulated results as per the criteria, and *CF* represents the favorability towards the cost functions involved.

Step 3: The decision matrix considering the ideal and anti-ideal values was further modified to form a normalized matrix *N* according to Eq. (4) and Eq. (5), where $N=[n_{pq}]$.

$$n_{pq} = \frac{a}{o_{pq}}\ if\ q\epsilon CF, \forall p \quad (4)$$

$$n_{pq} = \frac{o_{pq}}{a}\ if\ q\epsilon F, \forall p \quad (5)$$

Step 4: Further weighted matrix $Y= [y_{pq}]$of the normalized matrix was formed by considering weights as per Eq. (6).

$$y_{pq}=n_{pq} \times w_q \ , \forall\ p, q \quad (6)$$

Step 5: Utility degree of options, which presents the optimized result that is nearest to the favorable one, was calculated as per Eq. (7) and Eq. (8) for ideal (u_i^+) and anti-ideal (u_i^-) functions, respectively, where $r_p = \sum_{p=1}^{n} y_{pq}$.

$$u_p{}^- = \frac{r_p}{r_{ap}},\ \forall p \quad (7)$$

$$u_p{}^+ = \frac{r_p}{r_{ip}},\ \forall p \quad (8)$$

Step 6: The individual utility functions for anti-ideal and ideal solutions were formed as per Eq. (9) and Eq. (10), respectively.

$$f(u_p^-) = \frac{u_p^+}{u_p^+ + u_p^-}, \forall p \quad (9)$$

$$f(u_p^+) = \frac{u_p^-}{u_p^+ + u_p^-} \tag{10}$$

Step 7: The final utility function as per Eq. (11) was formed for each configuration by using individual utility functions of the ideal and anti-ideal utility functions. Thus, the function having the highest value for a particular configuration was ranked the highest and was obtained as the most optimized model.

$$f(u_p) = \frac{u_p^+ + u_p^-}{1 + \frac{1 - f(u_p^+)}{f(u_p^+)} + \frac{1 - f(u_p^-)}{f(u_p^-)}}, \forall p \tag{11}$$

The weights in Eq. (6) in Step 4 were calculated as per MEREC. In this method, the weights were calculated for different values and the higher weight was obtained for the criterion which affects the effectiveness of the options the most.

After the calculation of the normalized matrix, the final performance values *J* for the individual options were calculated as per Eq. (12) and were the logarithmic function of the normalized values considering all the affecting criteria.

$$\mathrm{J} = ln\left(1 + \left(\frac{1}{h}\sum_{q} \ln n_{pq}{}^{o}\right)\right), \forall p \tag{12}$$

After the calculation of individual performance values, the entire performance *G* of the options was calculated by removing each criterion every time according to Eq. (13). For instance, the performance of Option 1 with respect to Criterion 1 was evaluated by considering all other criteria, except for Criterion 1.

$$\mathrm{G} = ln\left(1 + \left(\frac{1}{h}\sum_{k,k\neq q} \ln n_{pq}{}^{o}\right)\right), \forall p, q \tag{13}$$

The absolute deviations were calculated for each criterion as per Eq. (14).

$$E_q = \sum_{p} |G - \mathrm{J}\,|, \forall q \tag{14}$$

Finally, the weights for Step 4 were calculated as per Eq. (15).

$$y_q = \frac{E_q}{\sum_k E_k}, \forall q \tag{15}$$

4. Results and Discussion

The different configurations for the system were simulated using search space, obtaining different results for each type of configuration, as shown in Table 4. Results using sensitivity parameters like inflation rate and discount rate were also analyzed.

According to the simulation in HOMER, 84 results were simulated, whereas 68 were the optimized results. Sixteen results were omitted due to the absence of a necessary converter in eight cases, the use of an unnecessary converter in four cases, and the capacity shortage constraints for the rest. All the combinations were prepared using the search space and simulated accordingly. All the configurations were compared based on different factors simulated like costs involved, amount of emissions, renewable fraction, energy generation, etc. The results of the main criteria or objective functions are summarized in Table 4.

According to the results obtained, the most optimized model is the model with PV+BG+B+C as the system, which has less NPC of \$728403, LCOE of 0.414 \$/kWh, and O&M costs of \$7525. The system has a feasible renewable fraction of 81.5%. In addition, the system has the least amount of emissions (e.g., the sum of the amount of carbon dioxide, carbon monoxide, particulate matter, unburned hydrocarbon, sulphur dioxide, and nitrogen dioxide), which is 350 kg/year compared to other systems. The optimization surface plot for the optimized model was plotted between battery v/s converter axes, as shown in Figure 4, with the darker region showing the optimized region and the diamond-shaped coordinates representing the simulated optimized values or the interpolated values.

Table 4. Simulated results of the system

Combination	PV (kW)	BG (kW)	B (kW)	C (kW)	NPC ($)	O&M cost ($)	CAPEX ($)	Ren. Fraction (%)	LCOE ($/kWh)	Emissions (kg/year)
PV+BG+B+C	150	400	100	150	728403	7525	102900	81.5	0.414	350.00
PV+B+C	150	0	100	150	739094	7579	95343	81.5	0.539	332.00
BG+B+C	0	400	100	100	775033	12233	83005	81.5	0.631	360.00
PV+BG+C	150	400	0	100	793725	15797	89387	81.5	0.701	367.00
BG	0	400	0	0	844790	17807	79005	81.5	0.89	489.00

Note: B indicates battery; C indicates converter; BG indicates biogas generator; CAPEX stands for capital expenditure; and Ren. fraction stands for renewable fraction.

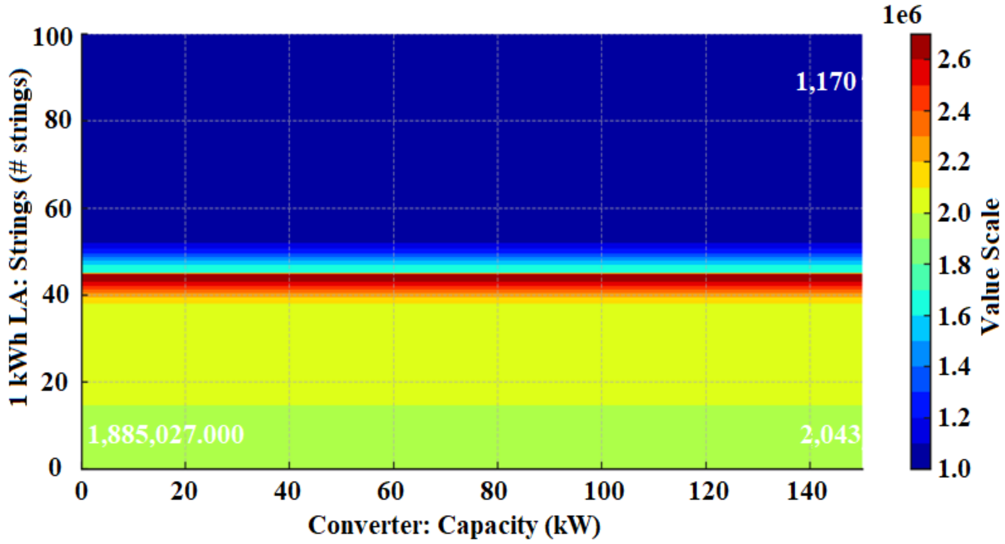

Figure 4. Optimization surface plot for total NPC

4.1 Electrical Analysis of the Optimized Model

The annual load consumption is 729696 units. The optimized model's yearly unit generation is 281696 kWh/yr by the PV system and 448000 kWh/yr by the biogas generator. Excess electricity of approximately 48084 units is sold, and the unmet load is below 0.018%. The monthly unit production by different energy resources is shown in Figure 5. The green and yellow regions show the unit generation by biogas generator and PV, respectively. A renewable fraction of 81.5% for the optimized model was depicted via the optimization surface plot, as shown in Figure 6.

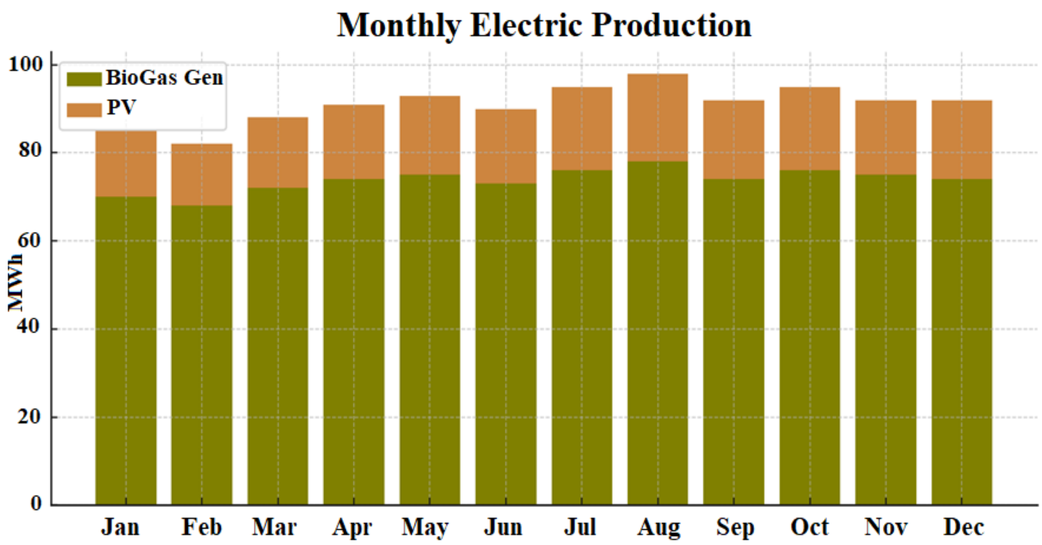

Figure 5. Monthly unit production by different resources

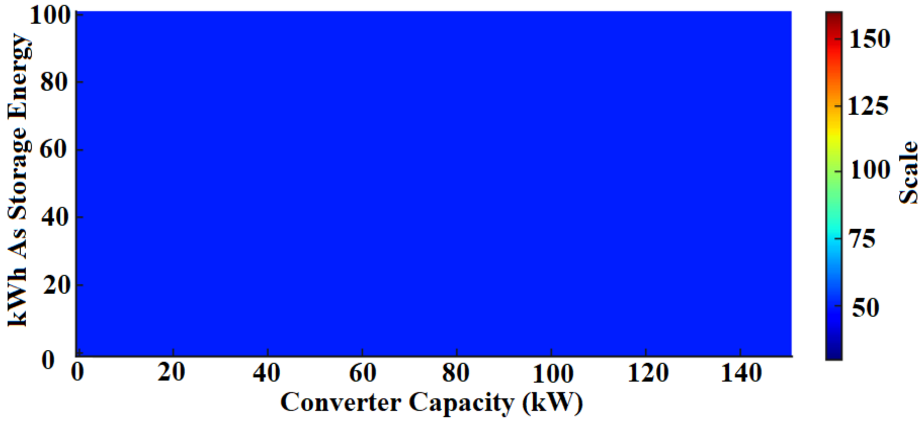

Figure 6. Optimization surface plot for a renewable fraction

4.2 Technical Analysis of the Optimized System

The data map (D-Map) for the PV power output of the optimized model is shown in Figure 7, where the highlighted region shows the output area of PV. Time series detailed analysis of the system is shown in Figure 8, where the different colors in the graph represent the concerned values of the time axis, i.e., according to the hour. The pulses similar to a rectangular shape (brown-colored) represent the contribution of PV; a round shape (red-colored) shows the contribution of the biogas generator; and small spikes (green-colored) show the contribution of the battery.

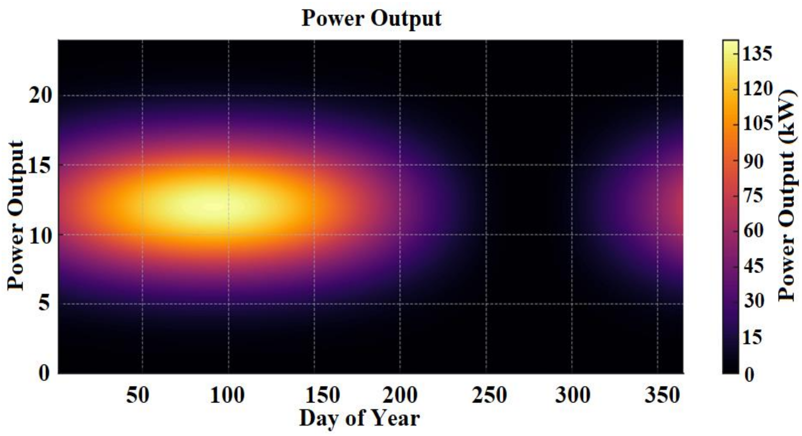

Figure 7. PV power output

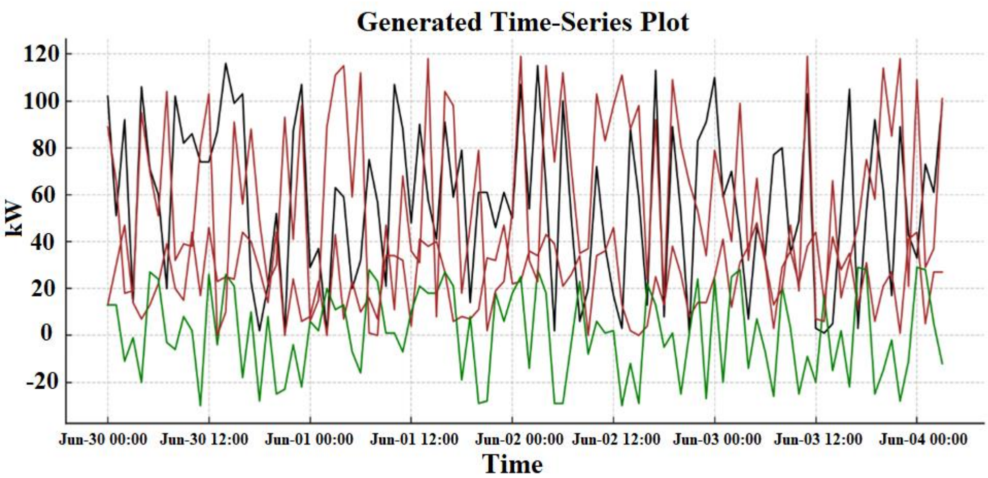

Figure 8. Time series detailed analysis of resources

4.3 Results of Sensitivity Parameters Used

The optimization surface plot for the optimized system obtained was plotted for the sensitivity parameters, i.e., inflation and discount rate, as shown in Figure 9. The inflation rate was taken from 2-8%, and the discount factor from 8-16%. The plot shows that the majority of the spectrum is covered by a system having PV+BG+B+C, which presents it as the optimized model in the presence of other systems according to Figure 10. The optimized values of NPC are shown as the diamond-shaped coordinates in Figure 11.

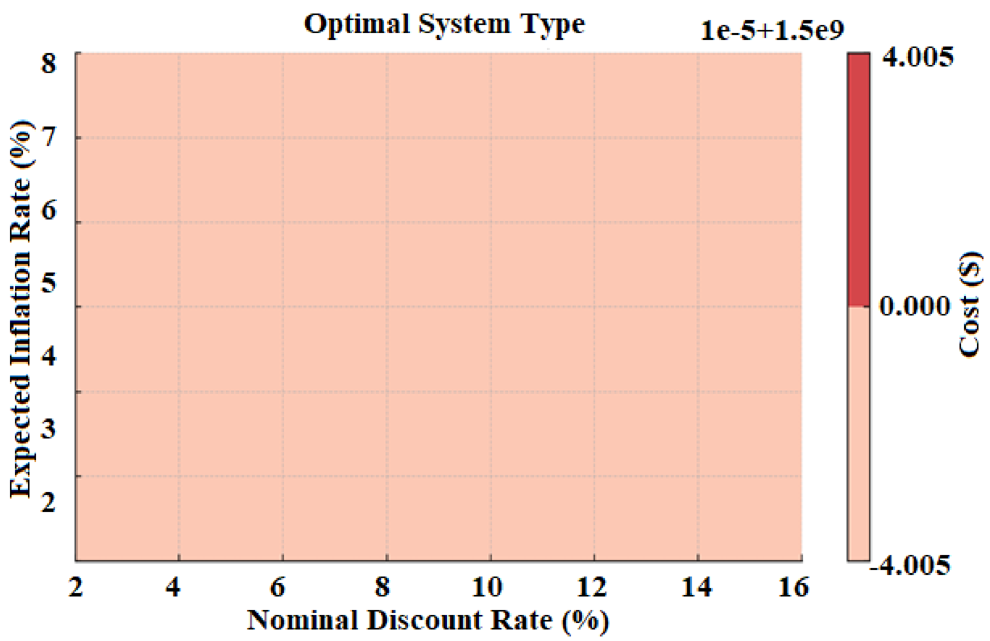

Figure 9. Optimization surface plot for inflation and discount rates between PV and biogas generator

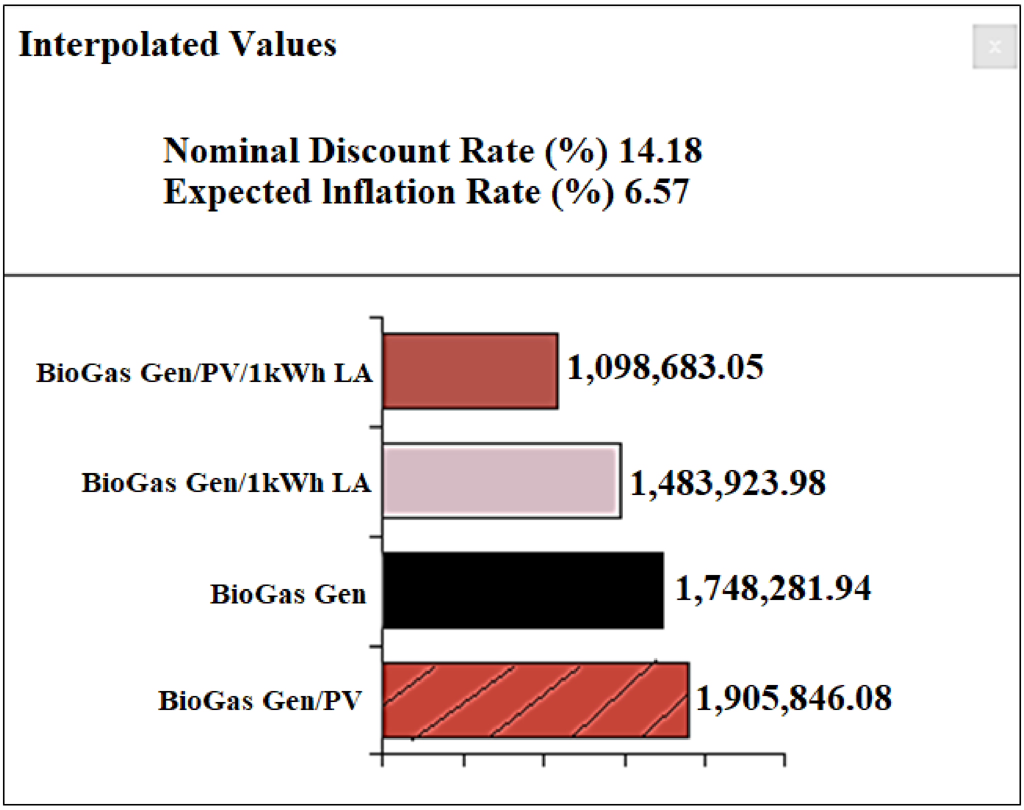

Figure 10. Operating region of different systems in the optimization surface plot

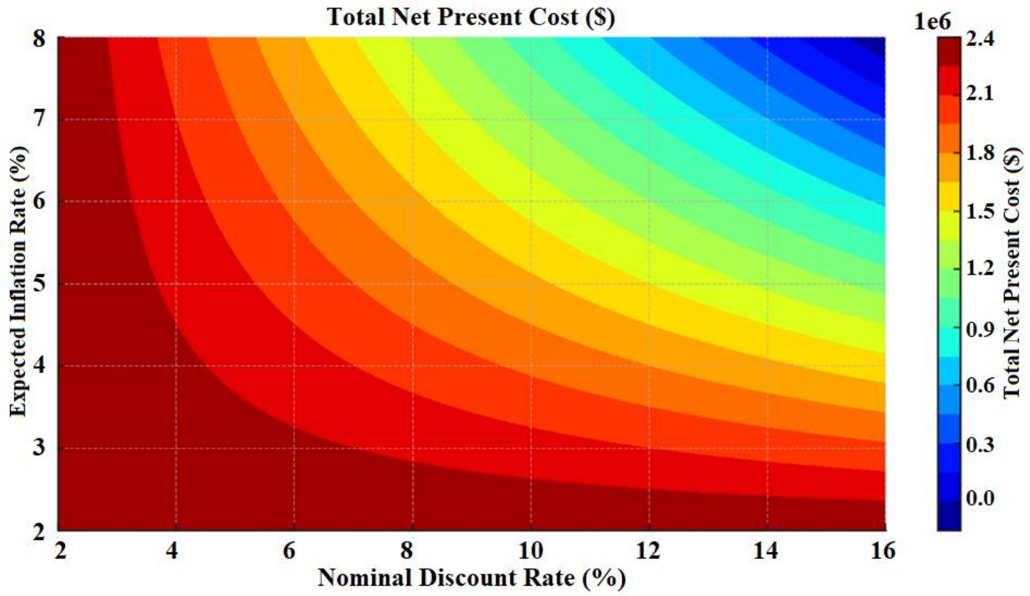

Figure 11. Optimization plot for NPC using sensitivity parameters

4.4 Amount of Greenhouse Gas Emissions

The amount of different greenhouse gases depends on the type of energy resource used. The comparison for the emissions was done between the systems having BG+PV+B+C and pure BG. The amount of emissions in kg/year for the optimized model is also shown via the optimization surface plot represented in Figure 12. The plot was plotted between PV and BG where the darker region shows the optimum region for the optimized model.

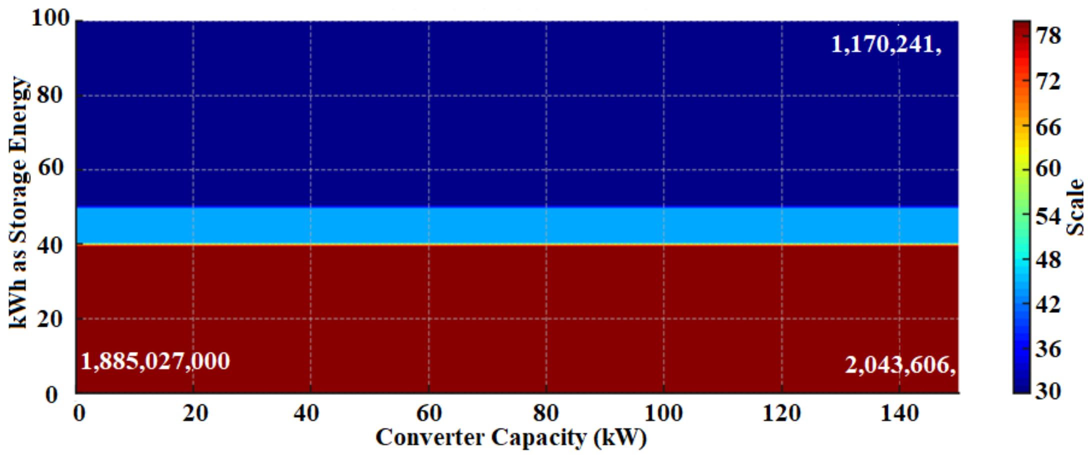

Figure 12. Optimization surface plot for emissions between PV and BG

4.5 Ranking of System Configurations Using MARCOS

The system considers PV+BG+B+C for energy generation. Thus, different configurations of the system were considered, i.e., Option 1 (O_1) -PV+BG+B+C, Option 2 (O_2)-PV+B+C, Option 3 (O_3)-B+BG+C, Option 4 (O_4)-PV+BG+C, Option 5(O_5)-BG. These five configurations (options) were compared and ranked according to the cost factors (criteria) like NPC (C_1), O&M costs (C_2), LCOE (C_3) and emissions (C_4), i.e., the configuration demonstrating the highest rank across these criteria was identified as the most optimized model. As per the methodology for the MARCOS technique, the decision matrix for the considered system is represented via Table 5.

Figure 13 shows that the MEREC method assigns different weights to the decision criteria based on their importance and applies them to four factors. C_2 carries the highest weight of 38%, making it the most critical factor in decision-making. C_3 has a weight of 31.8%, representing the average energy generation cost over the system's lifespan. C_4 has a moderate weight of 23%, indicating a compromise between cost-effectiveness and environmental concerns, whereas C_1 exerts the least influence of 7.2%. This distribution of weights implies that decision-makers emphasize long-term operational efficiency and affordability instead of initial capital costs while considering environmental sustainability.

Table 6 depicts the MARCOS ranking of various system configurations based on the overall performance. Each configuration was assessed using a *Ki* value, which indicates how close it is to the ideal solution, with higher *Ki* values signifying better performance. In the table, O_1 ranks highest with a *Ki* of 0.988, representing the optimal configuration. O_2, with a *Ki* of 0.922, also performs well, though it is slightly less efficient than O_1. O_3 and O_4 follow in third and fourth places, with *Ki* values of 0.722 and 0.643, respectively, suggesting moderate suitability. Meanwhile, O_5 is ranked lowest with a *Ki* of 0.527, making it as the least favorable configuration. This ranking system helps identify the most efficient system while balancing various criteria and trade-offs.

Table 5. Decision matrix of the system configurations

System Configurations		C_1	C_2	C_3	C_4
PV+BG+B+C	O_1	728403	7525	0.414	350
PV+B+C	O_2	739094	7579	0.539	332
BG+B+C	O_3	775033	12233	0.631	360
PV+BG+C	O_4	793725	15797	0.701	367
BG	O_5	844790	17807	0.89	489

Table 6. Ranks of the system configurations (options) by MARCOS

System Configuration	*Ki*	Rank
O_1	0.988	1
O_2	0.922	2
O_3	0.722	3
O_4	0.643	4
O_5	0.527	5

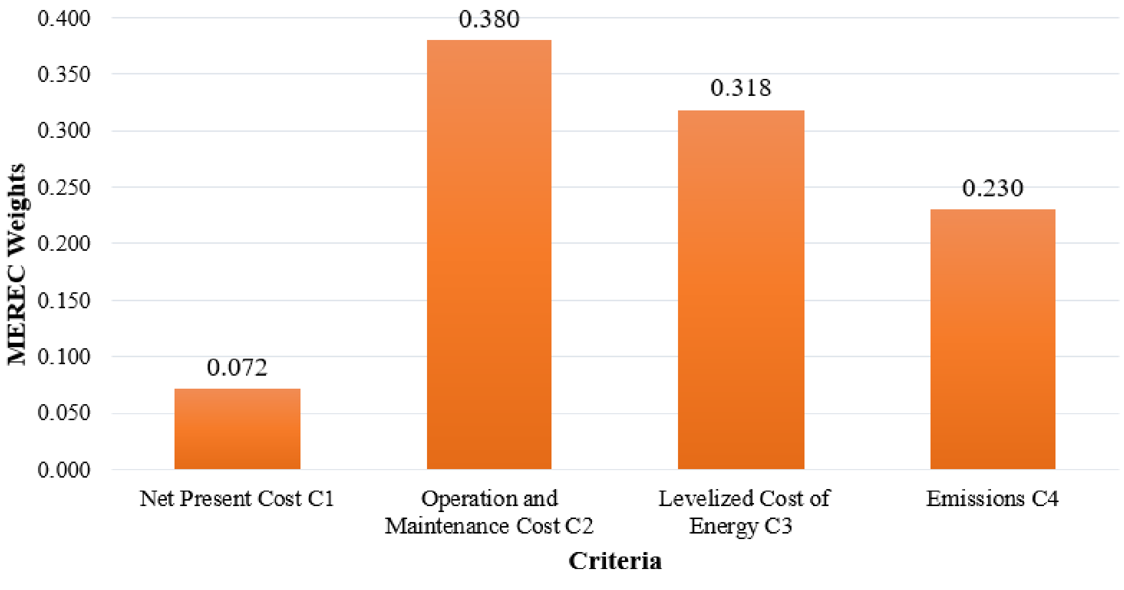

Figure 13. MEREC weights

The proposed HRES was considered for the case study of several micro and small industries in a village in Ludhiana. This system helps save fossil fuels and promotes the optimal use of RES such as solar and biomass energy. Using a biogas generator aids in fuel savings and enhances waste utilization, particularly in rural areas where waste treatment and proper disposal are significant concerns. Furthermore, RES facilitates distributed generation, reducing transmission costs and losses.

5. Conclusions

HRES for the case study considered was simulated using HOMER Pro. Different configurations of the resources were simulated in the search space. The configurations were compared based on criteria or objective functions, and the system satisfying all the objectives was considered the optimized one. The system was ranked according to the MARCOS technique, with the most optimized model ranked highest. Conclusions were summarized below using the results.

- According to the results, the system having PV+BG+B+C was simulated as the most optimized model as it had the least NPC of $728403 and O&M costs of $7525.
- The system's LCOE was 0.414 $/kWh, which is more desirable than other systems because it lowers electricity bills.
- The number of greenhouse gases released for the system with PV+BG+B+C was the least, i.e., 350 kg/year, compared to the system with BG only. Thus, it is the optimized model.
- The configurations were ranked according to the MARCOS technique. The system satisfying all the objective functions, i.e., the system having PV+BG+B+C, was ranked highest, which proved it to be the most optimized model compared to other configurations.

However, this study has some limitations. The system results may vary according to location factors. In addition, the system has not considered practical losses like constraints, transmission losses, converter losses, shading losses, etc. Therefore, the results may vary in practice. HOMER Pro provides easy simulation and optimization for practical cost analysis of the proposed system. As for future research, manageable costs and emissions analysis could be done for the load considered. The system could be simulated using different optimization algorithms. PV or biogas generators could be integrated with wind turbine systems for areas with more wind energy potential. Furthermore, different ranking techniques could be used and compared for the most optimized model.

Data Availability

The data used to support the research findings are available from the corresponding author upon request.

Conflicts of Interest

The authors declare no conflict of interest.

References

Ahmad, J., Imran, M., Khalid, A., Iqbal, W., Ashraf, S. R., Adnan, M., Ali, S. F., & Khokhar, K. S. (2018). Techno economic analysis of a wind-photovoltaic-biomass hybrid renewable energy system for rural electrification: A case study of Kallar Kahar. *Energy*, *148*, 208-234. https://doi.org/10.1016/j.energy.2018.01.133.

Akpahou, R. & Odoi-Yorke, F. (2023). A multicriteria decision-making approach for prioritizing renewable energy resources for sustainable electricity generation in Benin. *Cogent Eng.*, *10*(1), 2204553. https://doi.org/10.1080/23311916.2023.2204553.

Al Garni, H. Z., Awasthi, A., & Ramli, M. A. M. (2018). Optimal design and analysis of grid-connected photovoltaic under different tracking systems using HOMER. *Energy Convers. Manag.*, *155*, 42-57. https://doi.org/10.1016/j.enconman.2017.10.090.

Al-Ghussain, L., Darwish Ahmad, A., Abubaker, A. M., & Mohamed, M. A. (2021). An integrated photovoltaic/wind/biomass and hybrid energy storage systems towards 100% renewable energy microgrids in university campuses. *Sustain. Energy Technol. Assess.*, *46*, 101273. https://doi.org/10.1016/j.seta.2021.101273.

Ali, G., Musbah, H. N., Aly, H. H., & Little, T. (2023). Hybrid renewable energy resources selection based on multi criteria decision methods for optimal performance. *IEEE Access*, *11*, 26773-26784. https://doi.org/10.1109/ACCESS.2023.3254532.

Channi, H. K., Singh, M., Brar, Y. S., Dhingra, A., Gupta, S., Singh, H., Kumar, R., & Kaur, S. (2022). Agricultural waste assessment for the optimal power generation in the Ludhiana district, Punjab, India. *Mater. Today Proc.*, *50*, 700-708. https://doi.org/10.1016/j.matpr.2021.04.481.

Chowdhury, N., Akram Hossain, C., Longo, M., & Yaïci, W. (2020). Feasibility and cost analysis of photovoltaic-biomass hybrid energy system in off-grid areas of Bangladesh. *Sustainability*, *12*(4), 1568. https://doi.org/10.3390/su12041568.

Debnath, R., Mittal, V., & Jindal, A. (2021). A review of challenges from increasing renewable generation in the Indian power sector: Way forward for electricity (amendment) bill 2020. *Energy Environ.*, *33*(1), 3-40. https://doi.org/10.1177/0958305X20986246.

Dehshiri, S. S. H. & Firoozabadi, B. (2022). A new application of measurement of alternatives and ranking according to compromise solution (MARCOS) in solar site location for electricity and hydrogen production: A case study in the southern climate of Iran. *Energy*, *261*, 125376. https://doi.org/10.1016/j.energy.2022.125376.

Dinesh, P. & Sawle, Y. (2022). Optimization of hybrid solar, wind, and diesel energy system from cost analysis of micro-grid using Homer software. In In Emerging Electronics and Automation: Select Proceedings of E2A 2021 (pp. 161-172). Singapore: Springer Nature Singapore. https://doi.org/10.1007/978-981-19-4300-3_13.

El-Araby, A. (2023). The utilization of MARCOS method for different engineering applications: A comparative study. *Int. J. Res. Ind. Eng.*, *12*(2), 155-164. https://doi.org/10.22105/riej.2023.395104.1379.

Ghosh, M., & Acharyya, A. (2023). Solar energy adoption in India: A comparative analysis across states with a focus on West Bengal. *Praxis Int. J. Soc. Sci. Lit.*, *6*(5), 78-87. https://doi.org/10.51879/PIJSSL/060510.

Gupta, J., Nijhawan, P., & Ganguli, S. (2022). Optimal sizing of different configuration of photovoltaic, fuel cell, and biomass-based hybrid energy system. *Environ. Sci. Pollut. Res. Int.*, *29*(12), 17425-17440. https://doi.org/10.1007/s11356-021-17080-7.

Hiloidhari, M., Das, D., & Baruah, D. C. (2014). Bioenergy potential from crop residue biomass in India. *Renew. Sustain. Energy Rev.*, *32*, 504–512. https://doi.org/10.1016/j.rser.2014.01.025.

Hooda, D., Saraswat, S., Gakkhar, N., & Kumar, M. (2023). Assessment of solar-biomass power potential in the State of Punjab, India. *Adv. Sci. Technol.*, *130*, 173-179. https://doi.org/10.4028/p-q0lbYI.

Jahangir, M. H. & Cheraghi, R. (2020). Economic and environmental assessment of solar-wind-biomass hybrid renewable energy system supplying rural settlement load. *Sustain. Energy Technol. Assess.*, *42*, 100895. https://doi.org/10.1016/j.seta.2020.100895.

Ji, L., Liang, X., Xie, Y., Huang, G., & Wang, B. (2021). Optimal design and sensitivity analysis of the stand-alone hybrid energy system with PV and biomass-CHP for remote villages. *Energy*, *225*, 120323. https://doi.org/10.1016/j.energy.2021.120323.

Kaur, H., Kumar, R., Kumar, P., Kaur, S., Dixit, K. K., & Sharma, H. (2023). Efficient and cost-effective renewable energy integration of photovoltaic and hydro in rural India using HOMER Pro: A case study of Chupki, Punjab. *In International Conference on Intelligent Manufacturing and Energy Sustainability*, 281-291. https://doi.org/10.1007/978-981-99-6774-2_26.

Keshavarz-Ghorabaee, M., Amiri, M., Turskis, Z., & Antucheviciene, J. (2021). Determination of objective weights using a new method based on the removal effects of criteria (MEREC). *Symmetry*, *13*(4), 525. https://doi.org/10.3390/sym13040525.

Khan, M. R. B., Pasupuleti, J., Al-Fattah, J., & Tahmasebi, M. (2018). Optimal grid-connected PV system for a campus microgrid. *Indones. J. Electr. Eng. Comput. Sci.*, *12*(3), 899-906. https://doi.org/10.11591/ijeecs.v12.i3.pp899-906.

Kumar, P., Channi, H. K., Kumar, R., Prakash, C., Bhowmik, A., Pandey, S., Singh, A. K., Ali, M. M., & Soudagar, M. E. M. (2024a). Efficient integration of photo voltaic and hydro energy technologies for sustainable power generation in rural areas: A case study. *Mater. Sci. Energy Technol.*, *7*, 297-308. https://doi.org/10.1016/j.mset.2024.04.002.

Kumar, P., Pal, N., & Sharma, H. (2022). Optimization and techno-economic analysis of a solar photo-voltaic/biomass/diesel/battery hybrid off-grid power generation system for rural remote electrification in eastern India. *Energy*, *247*, 123560. https://doi.org/10.1016/j.energy.2022.123560

Kumar, R. & Channi, H. K. (2022). A PV-biomass off-grid hybrid renewable energy system (HRES) for rural electrification: Design, optimization and techno-economic-environmental analysis. *J. Clean. Prod.*, *349*, 131347. https://doi.org/10.1016/j.jclepro.2022.131347.

Kumar, R., Saha, R., Simic, V., Dev, N., Kumar, R., Kumar Banga, H., Bacanin, N., & Singh, S. (2024b). Rooftop solar potential in micro, small, and medium size enterprises: An insight into renewable energy tapping by decision-making approach. *Sol. Energy.*, *276*, 112692. https://doi.org/10.1016/j.solener.2024.112692.

Li, J., Liu, P., & Li, Z. (2020). Optimal design and techno-economic analysis of a solar-wind-biomass off-grid hybrid power system for remote rural electrification: A case study of west China. *Energy*, *208*, 118387. https://doi.org/10.1016/j.energy.2020.118387.

Malik, P., Awasthi, M., & Sinha, S. (2020). Study of grid integrated biomass-based hybrid renewable energy systems for Himalayan terrain. *Int. J. Sustain. Energy Plan. Manag.*, *28*, 71-88. https://doi.org/10.5278/ijsepm.3674

Mittal, V. K., Saxena, S., Kaur, V., & Singh, K. (2019). Analysis of biomass energy potential in Punjab. *J. Emerg. Technol. Innov. Res.*, *6*(5), 389–395. https://www.jetir.org/view?paper=JETIRCW06076

Murugaperumal, K. & Raj, P. A. D. V. (2019). Feasibility design and techno-economic analysis of hybrid renewable energy system for rural electrification. *Sol. Energy.*, *188*, 1068-1083. https://doi.org/10.1016/j.solener.2019.07.008.

Negi, H., Suyal, D. C., Soni, R., Giri, K., & Goel, R. (2023). Indian scenario of biomass availability and its bioenergy-conversion potential. *Energies*, *16*(15), 5805. https://doi.org/10.3390/en16155805.

Saha, R. K., Kumar, R., Dev, N., Kumar, R., Del Toro, R. M., Haber, S., & Naranjo, J. E. (2023). Structural modeling and analysis of fuel cell: A graph-theoretic approach. *PeerJ Comput. Sci.*, *9*, e1510. https://doi.org/10.7717/peerj-cs.1510.

Seedahmed, M. M. A., Ramli, M. A. M., Bouchekara, H. R. E. H., Milyani, A. H., Rawa, M., Budiman, F. N., Muktiadji, R. F., & Ul Hassan, S. M. (2022). Optimal sizing of grid-connected photovoltaic system for a large commercial load in Saudi Arabia. *Alex. Eng. J.*, *61*(8), 6523-6540. https://doi.org/10.1016/j.aej.2021.12.013.

Singh, B., Szamosi, Z., Siménfalvi, Z., & Rosas-Casals, M. (2020a). Decentralized biomass for biogas production. Evaluation and potential assessment in Punjab (India). *Energy Rep.*, *6*, 1702-1714. https://doi.org/10.1016/j.egyr.2020.06.009.

Singh, S., Chauhan, P., Aftab, M. A., Ali, I., Hussain, S. S., & Ustun, T. S. (2020b). Cost optimization of a stand-alone hybrid energy system with fuel cell and PV. *Energies*, *13*(5), 1295. https://doi.org/10.3390/en13051295.

Suresh, V. & Kiranmayi, R. (2020). Modelling and optimization of an off-grid hybrid renewable energy system for electrification in a rural areas. *Energy Rep.*, *6*, 594-604. https://doi.org/10.1016/j.egyr.2020.01.013.

Trung, D. D. (2022). Development of data normalization methods for multi-criteria decision making: applying for MARCOS method. *Manuf. Rev.*, *9*, 22. https://doi.org/10.1051/mfreview/2022019.

Ullah, Z., Elkadeem, M. R., Kotb, K. M., Taha, I. B. M., & Wang, S. (2021). Multi-criteria decision-making model for optimal planning of on/off grid hybrid solar, wind, hydro, biomass clean electricity supply. *Renew. Energy.*, *179*, 885-910. https://doi.org/10.1016/j.renene.2021.07.063.

Yimen, N., Monkam, L., Tcheukam-Toko, D., Musa, B., Abang, R., Fombe, L. F., Abbasoglu, S., & Dagbasi, M. (2021). Optimal design and sensitivity analysis of distributed biomass-based hybrid renewable energy systems for rural electrification: Case study of different photovoltaic/wind/battery-integrated options in Babadam, Northern Cameroon. *IET Renew. Power Gener.*, *16*(14), 2939-2956. https://doi.org/10.1049/rpg2.12266.