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Modeling and Economic Assessment of an Agricultural Microgrid: A Comparative Analysis

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***Abstract*—Sustainable energy resources are essential to meet the world's growing population and extending energy demands. Among the potential solutions, incorporating renewable energy sources into hybrid energy systems holds a lot of opportunities. This paper presents a design and economic analysis for an off-grid microgrid intending to power agricultural loads. Solar resources and PV-inverter system were modeled using pvlib-python, while the remainder of the microgrid, including the battery energy storage system (BESS) and biogas-based generator (BGG), was modeled and simulated using a custom dispatch method. The same system was modeled in Homer as well, and the outcomes of the designed microgrid were compared. When compared to Homer, the proposed approach reduced life cycle cost (LCC), and levelized cost of energy (LCOE) by 25%, and 20%, and emissions by 85%. In terms of generation, the proposed strategy reduced PV production by 20%, BGG output by 85%, and unmet load and surplus energy by 14% and 65%, respectively. The study additionally addressed an in-depth approach to modeling PV using various data sources and the associated modules and functionalities.**

***Index Terms*—Solar PV, Microgrid, Biogas, Energy planning, performance modeling.**

I. Introduction

Nonrenewable energy accounted for 84% of worldwide energy consumption in electricity, transportation, and heating in 2020 [1]. Renewable energy sources are growing more popular as a result of the depletion of fossil fuels and the adverse effects of climate change. Decentralized energy resources, also known as microgrids, are a widespread and resilient approach to integrating renewables into the conventional electricity system. Microgrids are a group of distributed generation units, loads, and storage systems that can operate in conjunction with the utility grid or independently [2]. However, the integration of renewables is subject to a variety of factors, such as economic impact and outcomes, ecological consequences, electrical feasibility, social acceptance, compliance with grid rules and regulations, market trends, and so on. The first step of microgrid design focuses on resource identification, system capacity sizing, and economic outcome assessment, which is then followed by electrical behaviors such as system stability in on-grid and off-grid operation. These processes can be completed before the physical implementation of the system using various mathematical modeling and simulation tools. Many microgrid optimization tools, for instance, are widely used by researchers to investigate economic and capacity optimization problems. The tools like Homer, PVsyst, RETscreen, and SAM are widely used to optimize renewables. Homer focuses on the economics of the microgrid by optimizing it for the lowest system cost. Homer provides a variety of renewable components and resources for designing and simulating hybrid systems [3]. In [4], [5], feasibility analysis for residential loads was performed using Homer, and a microgrid was simulated for various agricultural loads in [6], [7]. A microgrid for a remote school was also modeled in [8]. In addition, a hybrid microgrid for a Rohingya camp was modeled in [9]. In [10], a grid-connected hybrid microgrid system for an alluvial land was designed and optimized. Several methodologies were used to create the load profile for the microgrid. A ground source heat pump and horizontal axis closed-loop heat exchanger-based cooling system was created and simulated in [11] employing RETscreen with the goal of reducing emissions caused by conventional cooling systems in the tropical region. In [12], a grid-connected PV and biogas microgrid was designed. The authors also implemented the proposed system through a pilot setup and tested the microgrid controller's operation modes. A microgrid for the commercial load was modeled in [13], while in [14], a microgrid for residential load in an ecotourism area was developed using PVsyst and the results were compared with those from Homer.

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Pvlib-python is an open-source program that provides a collection of modules and functions for modeling and simulating PV systems. Pvlib allows for the implementation of various models of solar PV systems, as well as the manipulation of various input and output parameters such as solar position, clear sky modeling, Typical meteorological year (TMY) data to irradiance conversion, panel DC power, inverter power, and so on [15]. Several researchers have used pvlib-python to perform solar modeling, PV performance analysis, and resource prediction. In [16], different NOAA PV power forecast models were implemented in pvlib and compared to the Weather Research and Forecasting model configuration at the University of Arizona. Solar tracking and fixed PV arrays were both physically implemented [17]. The systems were also simulated in pvlib with the same parameters and compared to comprehend the way they operated. Similar work was also done in [18]. A calibrated PV panel was utilized to measure daily solar irradiation, and the results were compared to the pvlib results. The comparison showed that the results of pvlib were adequate for estimating PV generation. A PV system's power loss can be caused by a variety of factors. Shading, soiling, cell mismatch, and so forth. The losses caused by partial shading on a PV array were estimated using pvlib in [19]. For the calculation, a single-diode PV model was employed, and standard test conditions of the PV panel were taken into account. A spatial map of solar irradiation over a day was created in [20] using MATLAB and pvlib for agricultural purposes. The work also explored how irradiance affected various PV configurations.

The key goals of this research are to design a tool for modeling an off-grid microgrid system and evaluate its economic parameters and generation outcomes. The study aims to determine the long-term viability and financial viability of the microgrid system by examining economic characteristics such as initial setup costs, maintenance expenses, and possible revenue from surplus electricity generation. The utilization of the pvlib solar modeling tool in tandem with economic modeling is distinct in this study. The approach enables an in-depth and precise assessment of several scenarios, providing significant insight into the long-term economic feasibility of off-grid microgrid systems. The rest of the paper is organized in the following order, II. Methodology, III. Input Parameters, IV. Result Analysis and Conclusion.

II. Methodology

A. Microgrid Configuration:

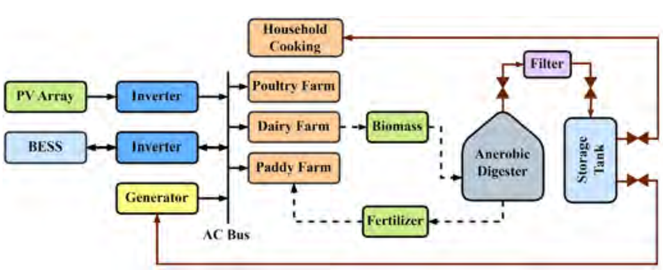

Fig. 1. Proposed standalone microgrid,

The microgrid in consideration was taken from [6]. However, the microgrid in the case study was considered for a grid-connected system intended to power a combined agricultural farm located at 22°41.5’N, 90°55.7’E. For this study, only an off-grid system was considered. The considered system is shown in Fig. 1. The microgrid consists of a PV array, AC-coupled BESS (Battery energy storage system), and a biogas-based generator (BGG) powering agricultural load.

TABLE I
SEASONAL RUNTIME AND CONSUMPTION BY DIFFERENT LOADS

Farm	Load	Rating (kW)	Runtime in different seasons (hour) Summer	Winter	Rainy Season
Paddy Field	LED lamp	0.05	10	12	10
	Irrigation Pump	3.73	4	2	2
	Submersible Pump	0.75	4	3	2
Dairy Farm	Fan (4)	0.3	9	0	0
	LED Lamp (4)	0.04	10	12	10
	Submersible Pump	0.75	2	2	2
Poultry Farm	Incandescent Lamp (4)	0.75	2	2	2
	Fan(3)	0.22	10	2	0
	Exhaust Fan(2)	0.08	2	2	2

The generator is powered by biogas produced from the waste from the farm. An additional gas container/storage tank was also considered to store a sufficient amount of gas for powering the generator during high load demand. The farm produces approximately 120kg of waste every day. The load demands for each farm are given in Table I. From the considered system two cases were considered, case-1: PV-BESS, Case-2: PV-BESS-BGG.

B. Process steps:

Fig. 2. illustrates the steps involved in the microgrid assessment process. The solar irradiation dataset was retrieved from the data source and preprocessed into a suitable format during the data preparation phase. The dataset was passed into pvlib, which generated annual solar energy generation. The unmet load was determined by comparing it to the annual load demand. The dispatch strategy then determined which component (BGG/BESS) would be used to satisfy the unmet load. Finally, economic factors were estimated depending on the generation outcome.

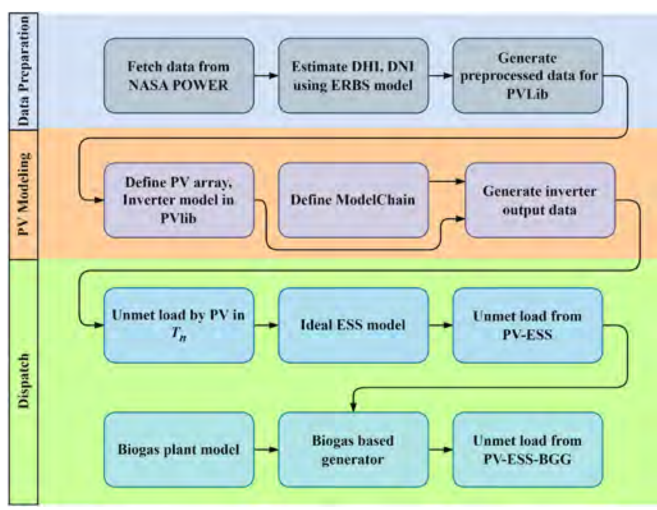

Fig. 2. Assessment steps and dispatch strategy

C. Solar Irradiation:

The core modeling of a PV system is based on various parameters ranging from estimating solar irradiation to modeling the PV array and inverter. Solar irradiation striking the earth's surface is influenced by a variety of factors such as air temperature, pressure, clouds, and so on. This impact must be considered when modeling a solar energy-based renewable system. To address these issues, various researchers have mathematically modeled these behaviors. The HDKR (Hay and Davies, Klucher and Reindl) model is a commonly used sky model in irradiation striking on a tilted surface on Earth. Equation (1) represents the HDKR model, and the other equations are supporting equation (1) [21], [22].

$$G_t = R_b(G_b + G_b A_i) + G_d(1 - A_i)\left(\frac{1+\cos\beta}{2}\right)\left[1 + f sin^3\left(\frac{\beta}{2}\right)\right] + G\rho_g\left(\frac{1-\cos\beta}{2}\right) \tag{1}$$

$$A_i = \frac{G_b}{G_o} \tag{2}$$

$$f = \sqrt{\frac{G_b}{G}} \tag{3}$$

$$G_{on} = G_{sc}\left(1 + 0.033\cos\frac{360n}{365}\right) \tag{4}$$

$$G_o = G_{on}\cos\theta_z \tag{5}$$

Where, G_t is incident solar radiation on PV array, G_b is beam irradiation (also called direct normal irradiance, DNI), G_d is diffuse irradiation (also called diffuse horizontal irradiation, DHI), G is global horizontal radiation at the earth's surface, G_{on} is extraterrestrial normal radiation, G_{sc} is solar constant, θ_z is zenith angle, A_i is anisotropy index, is the ratio of beam irradiation G_b and extraterrestrial irradiation G_o and β is the slope of the surface, ρ_g is ground reflectance, f is the horizon brightening factor, and n is the day of the year.

Beam radiation (DNI) and diffuse radiation (DHI) are the essential parameters for initial modeling. This can be obtained as TMY data from various meteorological data sources like NSRDB and PVGIS. Nevertheless, there is no up-to-date TMY data source for the selected location. As a result, the data was obtained from NASA POWER as GHI (Global horizontal irradiation). This data was then fed into the ERBS model for calculating DNI and DHI. The relationship between GHI, DNI, and DHI is represented by equation (6). Estimating diffuse radiation from the ERBS model can be done using equation (7) [23].

$$G = G_d + G_b\cos\theta_z \tag{6}$$

$$G_d = G \times f_d \tag{7}$$

$$k_t = \frac{G}{G_o} \tag{8}$$

When $k_t \leq 0.22$,

$$f_d = 1 - 0.09k_t \tag{9}$$

When $0.22 < k_t \leq 0.8$,

$$f_d = 0.9511 - 0.1604k_t + 4.388k_t^2 - 16.638k_t^3 + 12.336k_t^4 \tag{10}$$

When $k_t > 0.8$,

$$f_d = 0.165 \tag{11}$$

Where, f_d is the diffuse fraction and k_t is clearness index. After generating DNI, and DHI data, an input file was created to feed into pvlib ModelChain. The ModelChain class provides a streamlined input interface for modeling PV power from time series weather data [24]. The file lists hourly wind speed, and temperature data alongside GHI, DNI, and DHI values. Pvlib-python v0.9.4 was used in the assessment work [25].

D. PV modeling

Power generated by a PV array positioned at an optimal tilt angle is described in equation (12),

$$P_{PV} = C_{PV.STC}\, d\left(\frac{G_t}{G_{STC}}\right)\left[1 + \alpha_p(T - T_{STC})\right] \tag{12}$$

Where, $C_{PV.STC}$ is PV capacity (in kW) in standard test conditions, G_{STC} is incident irradiation at standard test conditions, α_p temperature coefficient of power, T is ambient temperature, T_{STC} is the temperature at standard test conditions, d is the derating factor. Losses for the inverter connected to the PV array shown in Fig. 1 are also considered.

E. BESS modeling

For the case of electrical energy storage, an AC-coupled BESS (ideal model) was taken into consideration. Setting a safe discharge limit in terms of state of charge (SOC) is necessary [26]. Because of this, the BESS's actual capacity is estimated using equation (13)

$$C_{ESS} = C_{nom(soc)} - C_{\min(soc)} \tag{13}$$

Here, C_{ESS} is actual/usable capacity, $C_{nom(soc)}$ is the nominal capacity, and $C_{\min(soc)}$ is capacity at minimum BESS SOC to enhance battery life. The maximum power that can be drawn from BESS is given in equation (14). Based on this equation the maximum available AC power from the BESS is given in equation (15). Similarly, the maximum charging current can be defined using equation (16), and the maximum power that went to BESS through the inverter's rectifier is given in equation (17)

$$P_{discharge(\max)} = V_{bat(nom)} \times S \times I_{bat(max)} \times P \times \sqrt{\eta_{rt}} \tag{14}$$

$$P_{out(max).ESS} = P_{discharge(\max)} \times \eta_{inverter} \tag{15}$$

$$P_{charge(\max)} = V_{bat(nom)} \times S \times I_{ch(max)} \times P \times \sqrt{\eta_{rt}} \tag{16}$$

$$P_{in(max).ESS} = P_{charge(\max)} \times \eta_{rectifier} \tag{17}$$

Where, $V_{bat(nom)}$ is nominal battery voltage, $I_{bat(max)}$ is maximum discharge current through the battery, $I_{ch(max)}$

maximum charging current, S is the series string size of the BESS and P is the parallel string size of the BESS, η_{rt} is round trip efficiency, $\eta_{inverter}$ is inverter efficiency and $\eta_{rectifier}$ is rectifier efficiency.

F. Biogas plant & generator model:

The biogas plant model was created using the results from [27]. With a hydraulic retention time of 40 days and a waste volume of 120kg per day from a dairy farm, the volume of the anaerobic digester (AD) should be 12m^3. In addition, the volume of the gas collecting chamber was calculated to be 6m^3. The average daily gas output is expected to be 4.8m^3, which needs to be moved to an additional gas tank to ensure a consistent supply for at least one week. This system additionally includes a 50m^3 gas tank for storing excess gas. The fuel usage at different loading conditions for the generator was derived from [28] and rescaled to meet the generator capacity used in this assessment. Based on the curve, the average gas consumption is 1.752 m^3/kW/h.

G. Microgrid Dispatch:

The microgrid dispatch approach is comparable to the load-following dispatch strategy used in Homer. The microgrid is initially powered by PV. If the PV system is unable to supply enough electricity at a given timestep, the required power is drawn from the BESS. If BESS fails to meet demand, the remaining power is supplied by a biogas-fueled generator. If the biogas is insufficient to cover that fraction of the demand, the load is indicated as unmet.

III. INPUT PARAMETERS:

TABLE II
INPUT PARAMETERS

System	Input Parameters	Value	Unit
PV	Panel efficiency	19.90	%
	Derated efficiency	86	%
	Inverter efficiency	97.5	%
	Ground reflectance	20	%
	Tilt angle	22.35	degree
	Azimuth angle	180	degree
	Capital Cost	461	$/kW
	Operating Cost	10	$kW/yr
ESS	Nominal capacity	10.2	kWh
	Usable capacity	8.19	kWh
	Max. Charging power	4.6	kW
	Max. Discharge power	4.6	kW
	Inverter efficiency	90	%
	Rectifier efficiency	95	%
	BESS round trip efficiency	90	%
	Capital Cost	168.23	$/kWh
	Operating Cost	5	$/kWh/yr
Generator	Average fuel consumption	1.752	m^3/kW/h
	Minimum load ratio	25	%
	Capital Cost	826	$/kW
	Operating Cost	0.030	$/op.hr

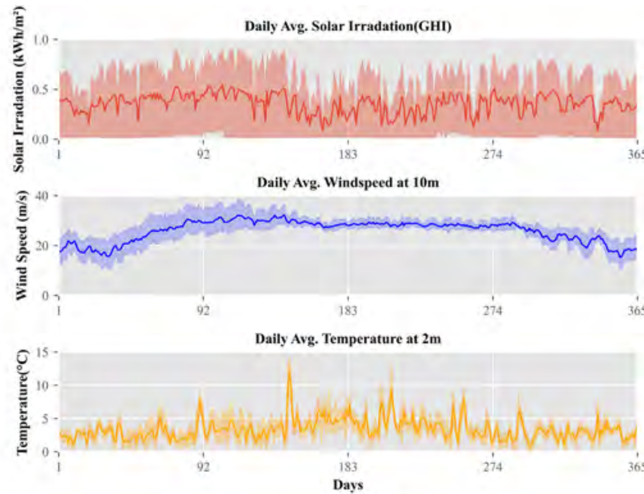

Fig. 3. Resources used in the assessment.

For solar resources, hourly irradiation data was taken from NASA POWER for the year 2021 [29]. The average solar irradiation for the selected location is 4.54 kWh/m^2/day. Additionally, temperature and windspeed data were also taken which are shown in Fig. 5. Aside from these, the input variables for the simulation were listed in Table II. The optimal tilt angle for the PV array was obtained from the findings of [30]. A load profile was created based on the loads listed in Table I, and it is shown in Fig. 4. The average daily load found was 21.64kWh and the maximum load observed was 4.28 kW.

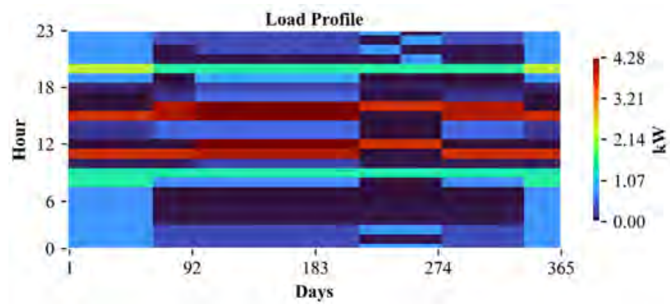

Fig. 4. Load profile for the combined farm.

IV. RESULT ANALYSIS

A. Sizing

The optimal size parameters for the particular load were selected based on minimum load loss. Table III shows the selected capacity of various components.

TABLE III
SIZING PARAMETERS

Component	Case-1: PV-BESS	Case-2: PV-BESS-BGG
PV capacity (kW)	7.2	7.2
Inverter capacity (kW)	7.2	7.2
BESS capacity (kWh)	10.2	10.2
BGG capacity (kWh)	0	4

B. GHI to DNI, DHI conversion

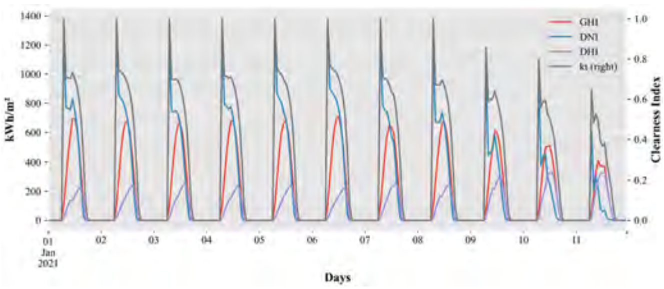

Fig. 5. GHI to DHI and DNI conversion through ERBS model.

Fig. 5 shows the input and output values for a few days of the described procedure of estimating DHI and DNI from GHI values using the ERBS model. Alongside the required outputs, the clearness index was also shown in the figure.

C. Solar Generation and Biogas Output

Fig. 6 depicts the generation graph. The PV array can provide power from 6 a.m. to 6 p.m. in the summer and 8 a.m. to 6 p.m. in the winter. When the PV and BESS are both unable to deliver the necessary power, the generator steps in to make up for it. It appeared that generators were largely used at night and throughout the summer when demand was high.

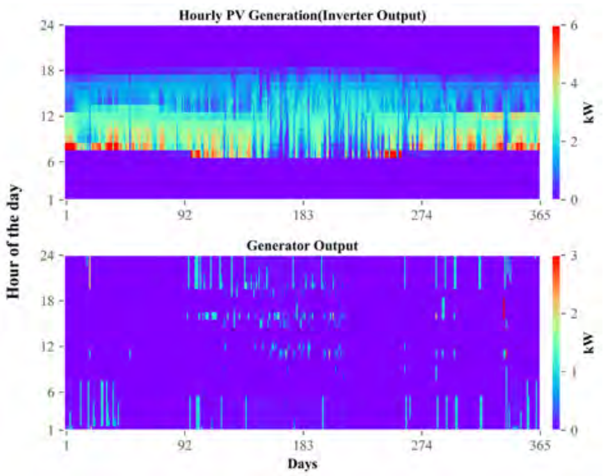

Fig. 6. PV generation and generator output.

D. BESS and Gas tank state

Fig. 7 depicts the percentage state for both battery and gas storage. The battery is usually discharged at night and in the summer when load demand is high; otherwise, the battery is recharged by the PV system throughout the day. Also, it appeared that the gas tank was being drained when the battery neared its lower limit, and the generator began to supply the demand. Also, in the gas storage graph, the storage tank is not filled for the first 40 days because the timeframe is considered a retention period.

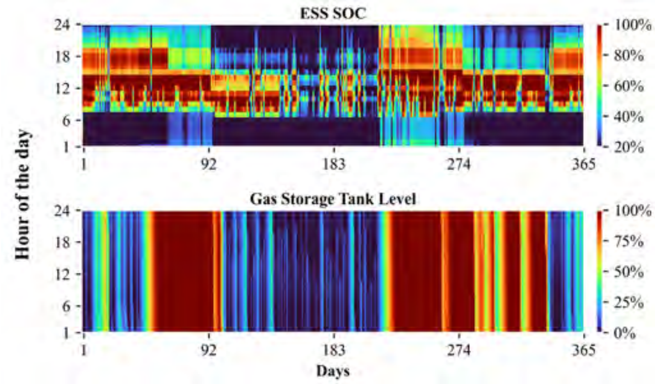

Fig. 7. Battery and gas storage tank state.

E. Comparison with Homer

Homer estimates solar PV generation using the HDKR sky model and ERBS model. Additional parameters such as PV, inverter, BESS, and generator specifications were maintained similarly for the Homer simulation as well. The important comparisons for both simulations are shown in Fig. 7 and 8. For PV generation, there is some variation in day-to-day output. It probably happened because some parameters didn't match completely. Additionally, the outputs for the generator will differ because the load following (LF) dispatch algorithm takes into account the generator output to be renewable since it's powered by biogas.

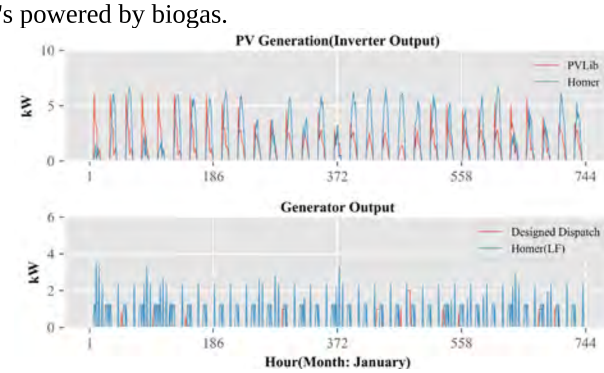

Fig. 7. PV generation and generator output comparison.

For annual generation, the proposed method matches Homer simulation quite closely for case-1 only. Also, in this situation, the BESS state matches precisely. Only case-1 has unmet loads since BGG in Case-2 can satisfy the demand properly. The unmet load of both simulations for case-1 is similar. As the PV power calculated by Homer is 20% higher, the surplus energy for Homer simulation is larger. However, these parameters no longer match in case-2 since the dispatch strategy is not similar to Homer for the included BGG. The proposed method reduced BGG output by 85% when compared to Homer. Furthermore, the unmet load (case-1) was lowered by 14%. In cases 1 and 2, the surplus energy was reduced by 45% and 65%, respectively.

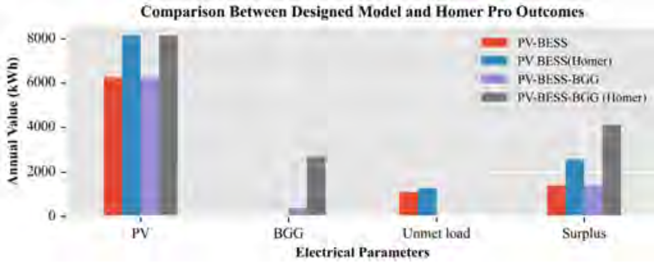

Fig. 8. Comparison of the cases simulated in proposed system and Homer.

F. Economic Outcomes

LCC and LCOE serve as key economic parameters in determining the cost-effectiveness of the proposed system. LCC is the difference between the present value of total revenue and the present value of total expenses throughout the project's lifetime, and LCOE is the cost per unit of electrical energy produced by the system. In addition to these, other economic parameters are listed in Table IV. In case-1, the proposed method lowered LCC, LCOE, and operation costs by 25%, 20%, and 64%, respectively, when compared to the results obtained using Homer. Case-2 lowered LCC, LCOE, and operational costs by 16%, 16%, and 57%, respectively.

TABLE IV
ECONOMIC OUTCOMES

Cases	LCC($)	LCOE ($/kWh)	Capital Cost($)	Operating Cost($)
Case-1(PV-BESS)	8027	0.08	5035	123
Case-1[Homer]	10722	0.10		349
Case-2 (PV-BESS-BGG)	12625	0.10	9166	156
Case-2 [Homer]	15102	0.12		360

G. Emission

Case-1 has no annual emission outcomes since there are no emission-generating components. Case-2, on the other hand, produces carbon emissions due to the inclusion of the generator. Annual emission values for different parameters are given in Table V. When compared to the Homer average emission was estimated to be 85%.

TABLE V
ANNUAL EMISSION

Pollutant	Case-2 (Homer) (kg/year)	Case-2 (kg/year)
Carbon Dioxide	26.98	3.84
Carbon Monoxide	0.362	0.051
Unburned Hydrocarbons	0.0160	0.0022
Particulate Matter	0.0022	0.0003
Nitrogen Oxides	0.340	0.0483

V. CONCLUSION

In this paper, a standalone microgrid was designed to cater to the agricultural load of a combined farm, incorporating a PV array, battery, and biogas-powered generator. The PV system in the microgrid was modeled using pvlib, while the rest of the microgrid and the dispatch algorithm were simulated using custom Python code. The pvlib library offered a straightforward and efficient approach to modeling the PV system's performance for the planned microgrid. To validate the results, a comparison was made with the Homer simulation. The results of the study showed that the designed PV-BESS system produced similar outcomes to those obtained through Homer simulation. The economic benefits were evident, with reductions of 16-25% and 57-64% in terms of life cycle cost (LCC) and levelized cost of energy (LCOE), respectively. Additionally, the generation parameters, such as unmet load and surplus energy, were reduced by 14% and 45-65%, respectively. The study highlighted the viability of pvlib and other open-source tools for designing and simulating hybrid renewable energy systems. It is found effective in evaluating the electrical performance, as well as the economic and environmental aspects of the planned microgrid. The fact that the results closely matched those of commercially and frequently used tools demonstrated the model's accuracy. For future study, the design of a grid-connected system and utilizing metaheuristic algorithms to optimize microgrid sizing can be explored. These potential additions could further enhance the microgrid's efficiency and overall performance.

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