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Research Article

Performance Evaluation of a Micro Off-Grid Solar Energy Generator for Islandic Agricultural Farm Operations Using HOMER

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A study was conducted to evaluate the performance of a 1.5 kW micro off-grid solar power generator in a 2-hectare area of a 23-hectare agricultural farm located in Camotes Island, Cebu, Philippines (10°39.4′ N, 124°20.9′ E). The area requires at least 3000 liters of water every day to irrigate its plantation of passion fruit and dragon fruit; however, there is no water source within the immediate vicinity that can support such requirement. A 1/2 horsepower water pump was installed to provide the required irrigation. A 1.5 kW solar photovoltaic (PV) system consisting of 6 units of 250-watts solar PV panel with corresponding 6 units of 200 ampere-hour deep cycle batteries managed by a 3-kW industrial grade inverter provided the power for the water pump and supplied for the electricity demand of the farm. The actual energy usage of the farm was measured from the built-in monitoring of the charge controller and the installed system was analyzed to determine its efficiency in meeting the actual load demand. The HOMER optimization tool was used to determine the optimal configuration for the micro off-grid system based on the actual load demand. Simulation results showed that the optimum configuration that could supply the actual load is a 2.63 kW all-PV system with 8 kWh batteries. Sensitivity analysis was done to consider (1) possible increase in electrical load when the current plantation expands either in progression or outright to its full-scale size of 23 hectares and (2) variations in fuel cost. This study can be considered a good model in assessing renewable energy needs of farms in the country, which can be operationalized for agricultural purposes.

1. Introduction

1.1. The Agricultural Sector and Its Challenges. Agriculture plays a pivotal role in various key issues we face today. Considered as one of the main sources of income, over a third of the worldwide population engage in farming for livelihood [1]. Agriculture is seen to facilitate poverty reduction in developing countries where investments in the sector have seen an increase [2]; to foster the global agenda on food security and improved nutrition [3]; and to cultivate economic growth and development [4, 5]. In the Philippines, 32% of the population is currently employed in the farming sector, making it one of the primary livelihoods of the country [6]. The sector is critical in the country's economic development by providing food, raw materials, products, and surplus labor [7].

However, the agricultural sector faces several challenges. The volatility of prices of farm produce, sustainability of agricultural practices, vulnerability of the sector to climate change, and the competition on land use are just some of the problems encountered. Agricultural water and irrigation management is one of its notable issues. Water scarcity and other environmental stresses prove to be a challenge for agriculture in Jining, China [8], whereas the optimal allocation of water for irrigation in the drier regions of Ghana was pointed out as a concern [9]. The divergence of water usage in wetlands and agricultural farms in various regions in China was also revealed as a challenge in a study by Zou et al. [10].

In the Philippines, agriculture is dominant in the rural areas [7], where access to water is a challenge. In a 2004 report, only 44% of the total irrigable area in the country is irrigated primarily due to insufficient water, hindering the country from meeting the increasing demand for agricultural products [11]. These rural areas also have very limited access to electricity, deterring installation of water pumps to help with irrigation. The scarcity of water and the limited access to electricity lead most farmers to resort to other sources to help them irrigate their farms. In most cases, building a small PV system to meet the pumping requirements of the land is the sensible solution [12]. Effective sizing of the components is also important to ensure a reliable, adequate, and economical design [13–17].

1.2. The Role of Renewable Energy in Agriculture. Water is an essential resource in agriculture. However, limited access to water in most farmlands in the Philippines proves to be a challenge to farmers in rural areas where most irrigable lands are located. Renewable energy, mostly coming from solar photovoltaic (PV) systems, is a solution that could solve such problems on limited resources. Numerous studies have been made where renewable energy is used to help in irrigation problems in the agricultural setting.

In Western Serbia, a group of researchers were able to devise a method of efficiently irrigating a raspberry plantation by testing a properly sized solar array and water pump, taking into account the depth of well, characteristic of the crop, and climate of the area. An accurate sizing of a 579 Wp photovoltaic (PV) system to a 1.0-ha raspberry plantation was established, irrigating the orchard efficiently. The sizing method was applicable only to farms of the same area, latitude, and climatic conditions [18]. Case studies from Kenya, Morocco, Chile, and India suggested that irrigation accounts for up to 60% of the production costs in farms as they consume around 2m^3 to 10m^3 of water per hectare per day. The solution to this problem was to use solar-powered irrigation, spurring an intensification of agricultural production in these countries [19]. Applications of solar-powered pumping in Turkey were more advanced as they used sun-tracking photovoltaic panels to draw maximum power from the sun, which fully automated the watering system using a microcontroller, solenoid valves, and soil moisture sensors. The area being irrigated is 0.8 hectares. There was no indication of the actual yield of the PV system and the actual amount of water being drawn out per day since this study was primarily aimed at integrating all the components to function as a stand-alone solar-powered automatic irrigation system [20]. A battery-coupled solar water pumping system was implemented in Malaysia with the aim of efficiently monitoring the irrigation of strawberry and rubber plantations that need frequent watering. The highlight of this study was the use of SCADA (supervisory control and data acquisition) control system to integrate 2 soil moisture sensors, 2 water level sensors as inputs, and 2 solenoid valves as outputs. The system successfully reduced issues on power consumption, system interface, and maintenance. The term battery-coupled means that when the sun's energy is absent or diminished, there is still a source of power from the battery; thereby irrigation is not compromised [21].

Most off-grid setups for irrigation systems are one-source systems where photovoltaic energy source is used. However, there has to be some alternative to solar power considering that weather conditions vary from day to day and power production may not be optimized on a daily basis. Thus, it becomes necessary to simulate other forms of energy source and add them to the energy mix, allowing for farm owners to decide which is the best package for their farm. Tropical islandic climate in the Philippines is unpredictable compared to Dunkirk, France's oceanic weather and Montana, USA's continental one, so there is a need to take weather variations into account [22]. HOMER is software that allows for such simulation and provides hybrid optimization models for electric renewables. It was developed by the National Renewable Energy Laboratory (NREL) to optimize microgrid design from village power to island electrification to even large power consumers that connect to the grid. It also evaluates if staying connected to the grid is economically advantageous than going off-grid [23]. HOMER is being used as a techno-economic optimization tool while comparing grid-connected, stand-alone, and diesel-powered homestead [24]. Incorporating photovoltaics, wind power, and biomass into hybrid systems can also be an option for farms with additional thermal energy demands for heating and cooking [25]. Such optimization tools can simulate overall system performance and do economic optimizations with criteria that include net present cost and the cost of energy [18–20]. Many off-grid [20–26] and on-grid systems [27–33] use HOMER as a tool to further scale up the capacity of a system and with varied energy use. A tabulated hybrid technology analysis using HOMER was created to show the various applications, the technology adapted, and the supply duration. It was found out that the hybrid setup is used mainly for household purposes but not in the agriculture sector [34]. HOMER can also play a big part in assessing the feasibility of large scale PV on-grid systems [35].

1.3. The Focus of the Study. This paper evaluated the performance of an installed 1.5 kW off-grid microgrid solar PV system in terms of its ability to meet the irrigation and other operational requirements of a 2-hectare plantation located in Camotes Island, Cebu, Philippines. The study aimed to (1) determine the ability of the system to meet the actual demand of the farm; (2) determine the appropriate sizing required for the actual demand through HOMERPro simulation; and (3) perform a sensitivity analysis in HOMERPro varying loads and fuel cost to assess system robustness.

2. Method and Materials

2.1. Method. Figure 1 presents the flow of the case study. An evaluation was conducted on a 1.5 kW solar PV installation in a 2-hectare farm using the actual energy usage obtained from the built-in monitoring of the charge controller. The measured load was then used and simulated through HOMERPro to determine the optimum configuration that could

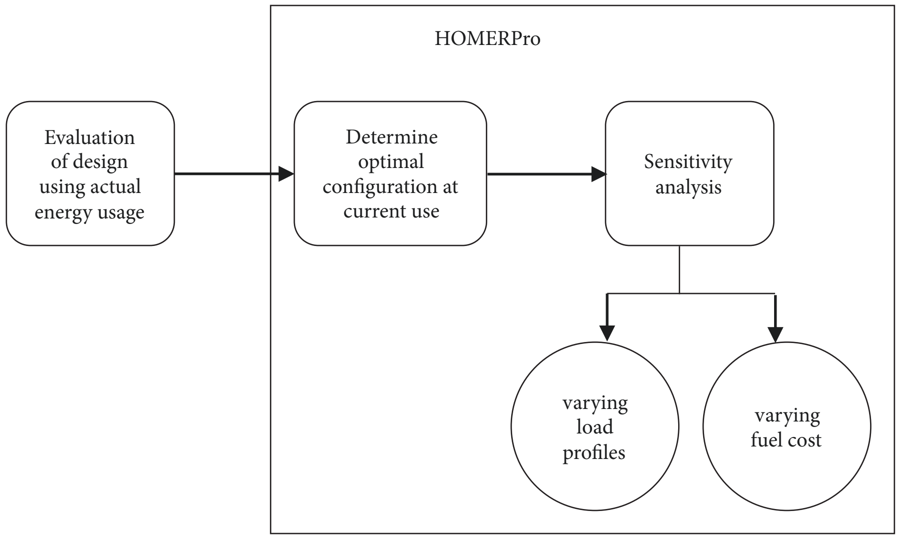

Figure 1: Research flow.

meet the actual load demand. Sensitivity analysis was done to test the robustness of the system when input variables were varied. Cases in islands and remote areas considered fuel cost, component cost, energy source, and electricity cost as uncertain parameters [36] while a study on a stand-alone hybrid energy system in a remote island in China considered load variations in the sensitivity analysis [37]. The sensitivity analysis for this islandic case study, however, considered only the variations in load and fuel cost. The current all-PV system only supplies electricity for the 2-hectare plantation and it is necessary to determine the ideal design when the farm will expand its operations. The island is also susceptible to fluctuations in diesel cost due to its location. This study did not consider any other renewable energy resources except solar energy.

2.2. Materials

2.2.1. Photovoltaic Power System. The photovoltaic power system is composed of an inverter, solar photovoltaic panels, solar charge controller, and battery. The components used in the actual installation were used in the simulation.

The off-grid photovoltaic inverter used is a SAKO pure sine wave inverter with battery charger and a built-in liquid crystal display (LCD) for easy monitoring. This is an industrial grade inverter capable of withstanding fluctuations in the battery current and has a low-battery protection. It functions both as an automatic voltage regulator as well as an inverter. The wide input voltage range is suitable for the unpredictable island weather [38].

The 6 series-connected PV panels are Renesola Virtus II with 250 watts maximum output power taken at 1000 W/m^2 solar irradiance. The datasheet by Renvu Solar Equipment Distribution (Renesola) stated that the efficiency of the panels will vary from 15.8 % to 16.0 % with irradiance ranging from 200 W/m^2 to 1000 W/m^2. The PV material and workmanship has a 10-year guarantee while the linear output power should be constant up to 25 years [39].

The solar charge controller is an Epsolar etracer series with a maximum current capacity of 60 amperes. It has a data logging capability of up to 450 days. The data for battery voltage, PV voltage, battery current, energy generated, state of charge, battery state, charging state, ambient, and battery temperature are supported by a timestamp every 20 minutes [40].

A solar-powered street light was also installed to illuminate the farm during night time (see Figure 2). In this context, solar street lighting should be used instead of grid-connected luminaries in cities as they are more sustainable [41, 42]. This Camotes system's 48V setup is almost similar to Thailand's off-grid experiment on 4 regions, although Thailand's setup suffers from shading due to trees on the 2 regions while the Camotes farm setup is free of growing trees as the PV panels are on a 10-meter hill [43]. If crops are tomatoes, the PV panels need to be as close to the ground as tomatoes needs as much sunshine as well [44].

2.2.2. Water Pump. The 1-phase AC water pump is a Goulds 1/2 hp convertible jet pump, initially a shallow-well pump but fitted with deep-well accessories (see Figure 3). A DC pump was not used here like the one used in a small farm in Egypt [45] as a DC pump is dependent on the availability of the sun in order to pump water. An existing 3-phase AC water pump is even more efficient running on solar PV operating the maximum power point tracking method [46]. The MPPT method can also be used for off-grid lighting system [47] and on typical DC solar home systems, on-grid, off-grid, and hybrid systems as well, all governed by the standard DIN EN50530 [48].

The well required 3 lengths of 20-foot 2-inch pipes to reach the water table. Operating at a working pressure of 30 psi, it can pump out 600 liters per hour. The aim here is just to regard the AC water pump as an ordinary electrical appliance that can be turned on and off anytime.

(a) (b)

Figure 2: Solar street lamps for (a) farm lighting and (b) the 6-panel PV installation.

Figure 3: Water pump at work in Camotes farm, Cebu, Philippines.

2.2.3. Weather Data. In the HOMER Pro Microgrid analysis tool, the meteorological data were taken from a solar, wind, and temperature database (NASA Surface Meteorology and Solar Energy database) and were made available in the simulation page. The coordinates of the Camotes installation (10°39.4′ N, 124°20.9′ E) served as input to the said tool to consider exact location as solar irradiation can vary from one city to another [49].

2.2.4. Simulation. Simulation and sensitivity analysis were done using the HOMERPro software. The software is the latest bundled pack with advanced storage, multiyear, and MATLAB link option. An optimizer returns for the optimum net present cost and cost of energy. The load profile from the farmhouse was inputted as a single electrical load averaging at 5.35 kWh/day throughout the year. Though water pumping is commonly referred to as a deferrable load, in the actual farm operation, it was considered as just an electrical appliance that can be turned on and off whenever water was needed either for irrigation or for household consumption. The solar panel used the figures from the installed PV panels with 0.4%/°C as temperature effects on power. The nominal operating cell temperature was 45°C and its efficiency at standard test conditions is 15.4%. In the economic analysis, diesel fuel price was set at US$0.9/liter. Nominal discount rate was set at of 4%, 8%, and 16%. The expected inflation rate was 3% and the project lifetime was set at 25 years. Annual capacity shortage was set at 5%.

2.3. Research Environment. The off-grid PV system was installed in a dragon fruit and passion fruit farm located in Camotes Island, Cebu, Philippines. Although, the total farm area is approximately 23 hectares, the initial cultivated land is around 1 hectare for each fruit. Passion fruit stems are guided up to a trellis with supports that are equidistant to each other while dragon fruits are from the cactus family and are separately planted and supported by a concrete post (see Figure 4).

3. Results and Discussion

3.1. Load Profile of the Farm. Electricity consumption of the 2-hectare farm was mainly attributed to irrigation, lighting, and household appliances like mobile phone chargers, television, and radio. The actual energy usage of the farm was obtained from the built-in monitoring of the charge controller. The actual system generated a total of 433.357 kWh on its first 81 days of operation or an average of 5.35 kWh/day. Figure 5 shows the daily energy produced over the observation period.

Of the total production for the 81 days, 198.7 kWh charged the battery while simultaneously powering an electrical load of 234.657 kWh. An average of 2.453 kWh/day was consumed to charge the battery bank. Figure 6 shows the daily energy generated to charge the battery, as seen by the solar charge controller.

FIGURE 4: Passion fruit (left) and dragon fruit (right) plantations in Camotes, Cebu.

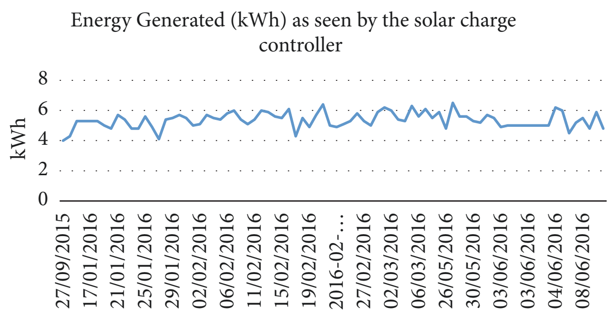

FIGURE 5: Daily energy generated (81-day observation).

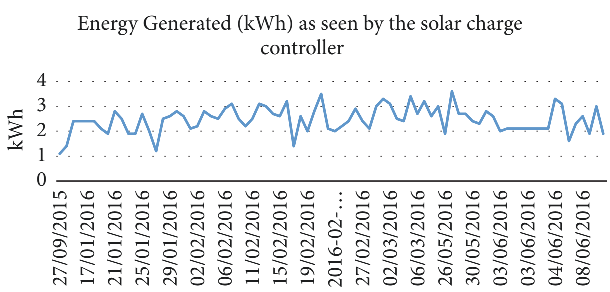

FIGURE 6: Daily energy generated to charge the battery (81-day observation).

3.2. Evaluation of Installed 1.5kW Solar PV Microgrid. The 1.5kWp PV system was used to power (1) the water pump using a 1/2 horsepower convertible jet pump for irrigation, (2) the installed solar street light, and (3) various household energy requirements of the farm. The system capital cost for the existing system was roughly US$2,885. Although the system was running to meet irrigation and other operational requirements of the farm, simulation shows that the system is not at optimum configuration. Table 1 shows the feasible configurations per HOMERPro simulation for the current load demand of the farm.

The optimum configuration with the lowest net present cost at US$ 8,405 and lowest cost of energy (COE) at US$ 0.202 is an all-PV 2.63 kW with 8 kWh battery installation. This configuration produces 3,869 kWh/year with excess electricity at 40.2% and unmet electrical load of 3.61%. Figure 7 shows the PV power output of the system.

Autonomy of the optimum system is 21.5 hours. The battery's nominal capacity is 8.01 kWh with usable nominal capacity of 4.80 kWh. Figure 8 shows the state of charge of the battery.

The optimal system is compared economically with operating only a 1.1 kW diesel generator set, which has the lowest initial capital cost among the feasible configurations. The results showed that the optimal system has a return of investment of 38.9%, internal rate of return of 44.8%, and discounted payback of 2.18 years.

3.3. Sensitivity Analysis. Sensitivity analysis was done on the optimum design, varying the load and the diesel fuel cost. The load considered did not include the energy generation for battery charging and was projected to increase with the increase of land area to farm. Load variations were computed at increases of 20%, 40%, 60%, 80%, and 100% of land area (see Figure 9).

The initial diesel fuel cost was US$ 0.9/liter. Variations in diesel fuel cost were computed considering price fluctuations of diesel in the Philippines for a one-year period from October 25, 2017, to October 16, 2018 [50]. The median (0.96%), maximum (16.62%), minimum (-5.98%), and average (0.86%) percentages were applied to vary the costs. Figure 10 shows the percentages of oil price fluctuations for the period considered.

The analysis was run at 4%, 8%, and 16% discount rates. Figure 11 shows the results of the analysis when discount rate is set at 4%. As both load demand and diesel cost increase, all-PV installation will still be optimal.

The same is true when discount rate is set at 8%, where an all-PV installation would still be optimal at varied loads and diesel cost. Figure 12 shows the result of the analysis.

However, when the nominal discount rate is set at 16%, optimum configuration when the farm expands to its full operational size of 23 hectares given that diesel price is low is a combination of diesel generator and solar PV. All-PV would still be optimal at 20%, 40%, 60%, and 80% increase in land area at different values for diesel cost and for full-size operations at higher diesel costs. Figure 13 shows the result.

Table 1: Feasible configurations at 5.35 kWh/day load demand.

PV	Generator	Battery	Converter	COE	NPC	Initial Capital
2.63kW		8kWh	0.810kW	US$ 0.202	US$ 8,405	US$ 3,255
2.59kW	1.10kW	7kWh	0.849kW	US$ 0.225	US$ 9,696	US$ 3,238
	1.10kW	5kWh	0.798kW	US$ 0.556	US$ 23,999	US$ 1,080
5.25kW	1.10kW			US$ 0.679	US$ 29,320	US$ 3,921
	1.10kW			US$ 0.806	US$ 34,793	US$ 140.78

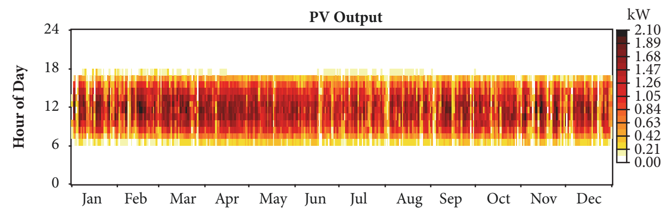

Figure 7: PV power output, 2.63kW all-PV (optimum).

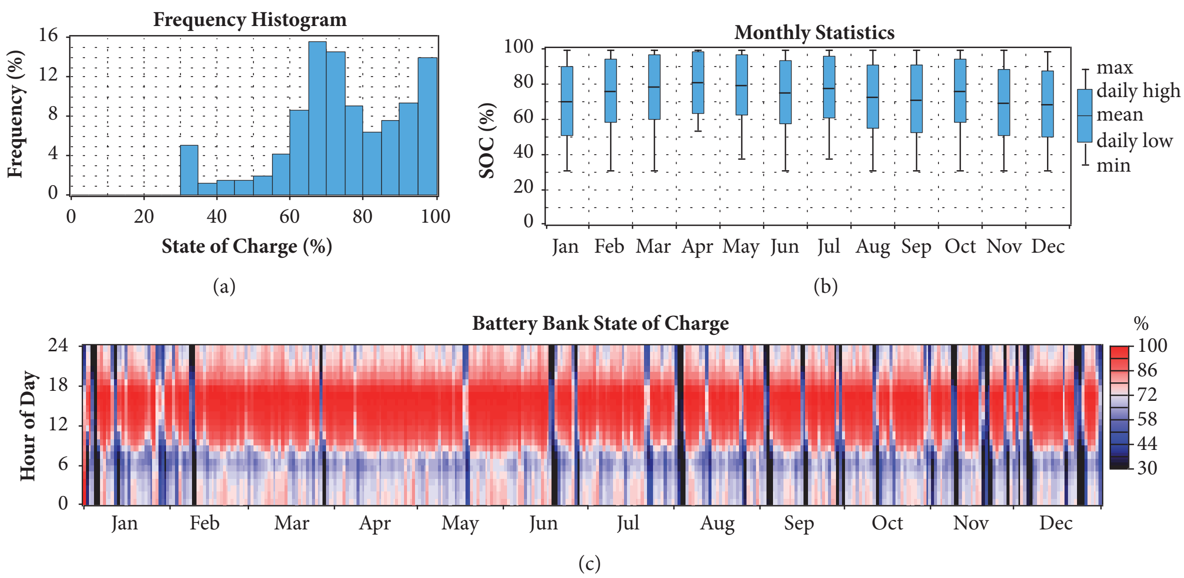

Figure 8: State of charge of battery, 2.63 kW all-PV (optimum).

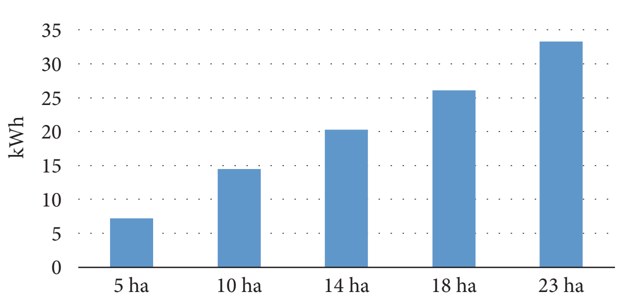

Figure 9: Projected load variations at increments in land area.

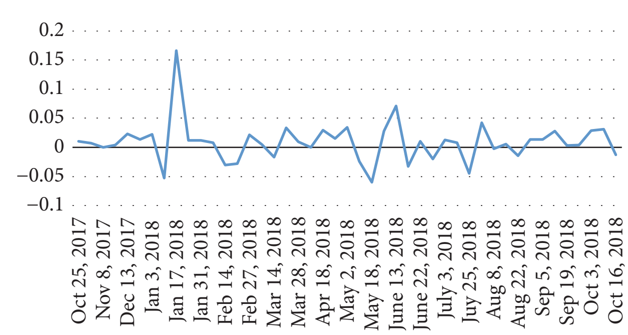

Figure 10: Oil price fluctuation (October 25, 2017, to October 16, 2018).

4. Conclusions

A 1.5kW solar PV was installed in a 2-hectare farm in Camotes to power its 1/2 horsepower water pump for irrigation and to supply electricity for its operations and other household requirements. The measured energy usage per the built-in monitoring of the solar charge controller averaged 5.35 kWh/day. HOMERPro was used to determine

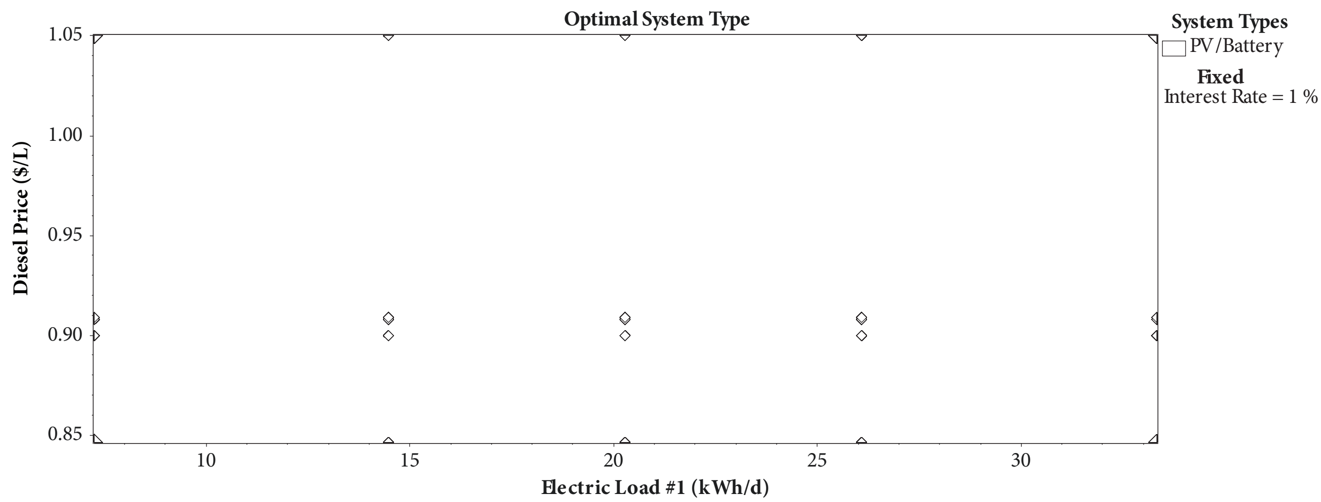

Figure 11: Sensitivity analysis at 4% nominal discount rate.

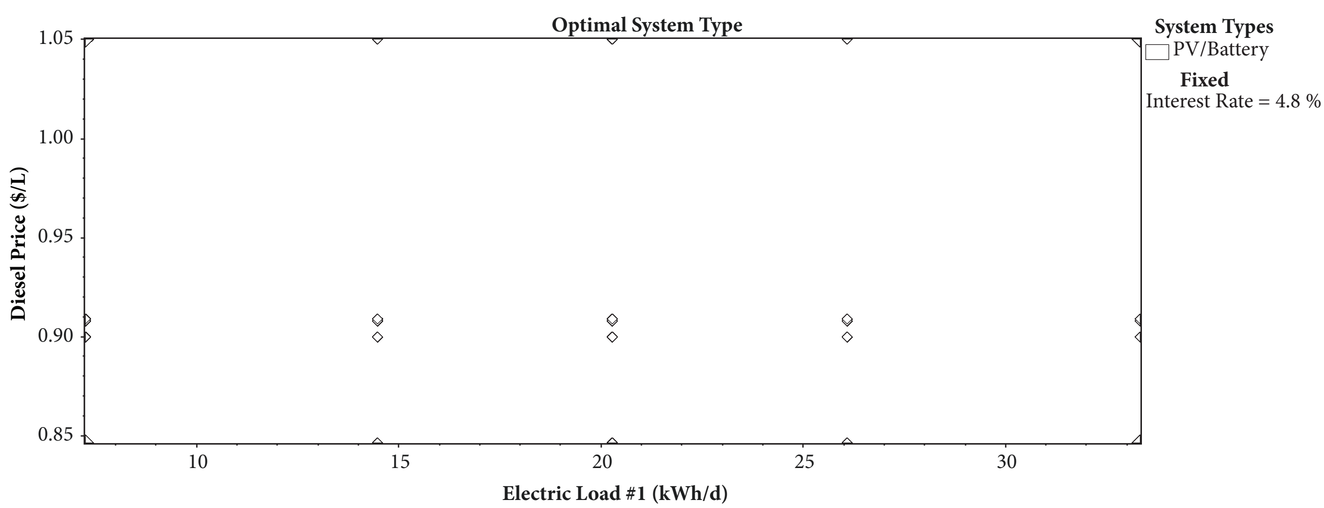

Figure 12: Sensitivity analysis at 8% nominal discount rate.

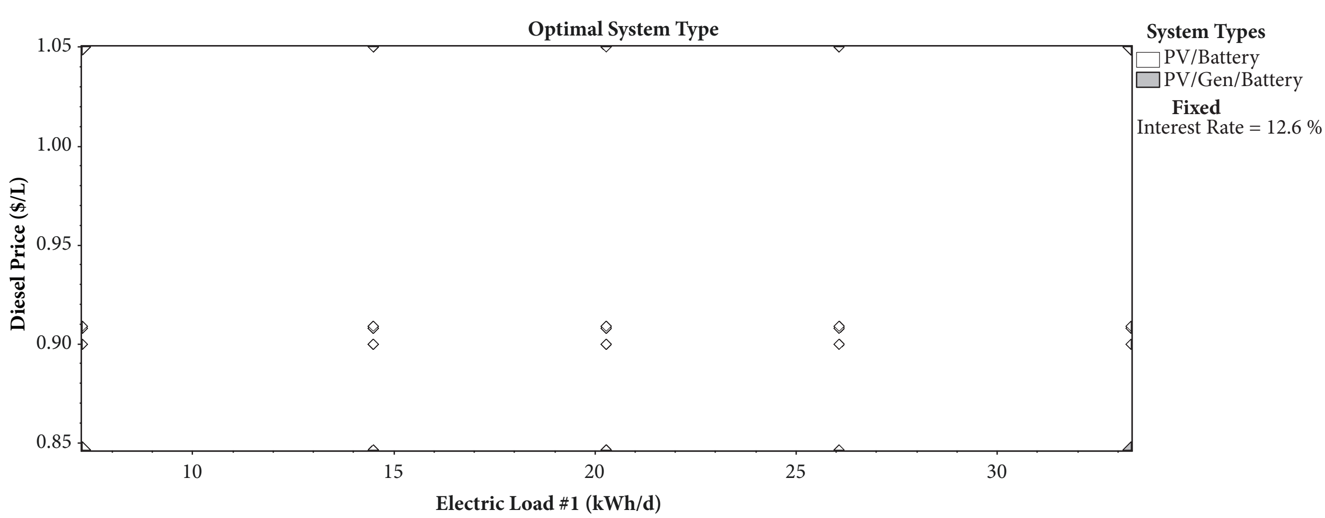

Figure 13: Sensitivity analysis at 16% nominal discount rate.

the optimal configuration that would satisfy the actual energy usage of the farm. Simulation results showed that the optimal configuration is a 2.63kW PV and 8kWh battery installation with COE of US$0.202 and net present cost of US$8,405. Sensitivity analysis, varying the load demand and diesel fuel prices, indicated that, at 4% and 8% discount rate, an all-PV system would remain optimal while at 16% discount rate, a hybrid system of PV and diesel generator would be optimal at higher diesel costs while an all-PV system would remain optimal at lower diesel costs. The results of the study provided for a good model that can be used in evaluating the renewable energy needs of farms in the country.

5. Recommendations

The case study considered only solar energy as the renewable energy resource. Adding other sources of renewable energy to determine optimal configurations and to test the sensitivity of the optimal system is recommended for future studies. The load demand profile of the farm was averaged to simplify calculations. Classification of loads and determining how these loads differ on a daily basis are recommended for further studies. Irrigation and the management of water resource on the farm could also be considered.

Data Availability

Research data will be provided upon request.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

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