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Article

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Microgrid System Evaluation Using Capacity Factor For an Off-grid Community in Nigeria

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ABSTRACT

With the high rate of economic development, there is an increasing load demand even in rural communities and Obayantor in Nigeria. Obayantor, having zero connection to the primary grid, needs an alternative source of electricity. Following the community located in a tropical regoin of Nigeria, it has enough solar energy that could be harnessed for electricity generation. With the high price of diesel fuel, solar microgrid seems to be the best energy solution for the rural community. In this study, technical and economic analysis was carried out on the solar-based microgrid and compared with a diesel-only microgrid using MATLAB Software tool. The results showed that the solar microgrid was cost-effective and affordable for the rural community compared with the diesel microgrid, which is more expensive to afford. The Annual system cost for the solar microgrid was lower compared with the diesel source. The result also revealed that the diesel-alone microgrid system is 4.71 times and 0.2 times more costly than the solar-based microgrid system in terms of energy and Annualized System costs, respectively. This made the diesel microgrid not to have technical and economic feasibility for the community.

Keywords: Microgrid, Net Present Cost, Capacity factor, Simple Payback Period, Cost of Electricity
JEL Classifications: Q2, Q42, P51

1. INTRODUCTION

Electricity is the life wire of the economic growth and development of any nation. About 1.6 billion people living in isolated regions worldwide have no access to electricity, resulting in energy poverty (Jiang et al., 2020). Chances for economic development are a result of access to electric power (Ali et al., 2021) (Amuta et al., 2021). Renewable energy sources are gaining more awareness globally due to global warming and are considered for electricity in homes and rural locations without access to electricity (Energy Access Outlook, 2017) (Orovwode et al., 2021). The minimum cost of energy in a microgrid can be determined by economic evaluation. Therefore a technical and financial analysis on microgrid is vital to determine if its deployment is economically feasible when implemented. Generating more energy from resources that can be cost-effective and contributing less to climate change or having adverse effects on the environment has been the focus of researchers presently (Habibullah et al., 2017) (Amuta et al., 2018)

(Astriani et al., 2019) considered techno-economic evaluation of a small-scaled microgrid with of Solar-PV and storage battery energy source that could improve reliability. The result showed that the microgrid was cost is economically feasible when equipped with modern technology for control. The authors considered only Net Present Value and Internal rate of return economic indices. (Sommerfeldt and Madani, 2017) proposed a Monte Carlo method to present the techno-economic evaluation using Solar Photovoltaic for the Swedish residential area. The result showed that the Solar PV investor would have a 71% opportunity to get a real return of 3% on investment, while the possibility dropped to 8% without subsidies.

The authors in (Cani et al., 2017) presented the feasibility and economic analysis of the sugar can power plant industry with renewable energy resources. The methodology implemented Homer Pro software in the existing and proposed structure considering the payback time. The result of the optimized plant configuration gave a shorter payback time compared to the proposed plant.

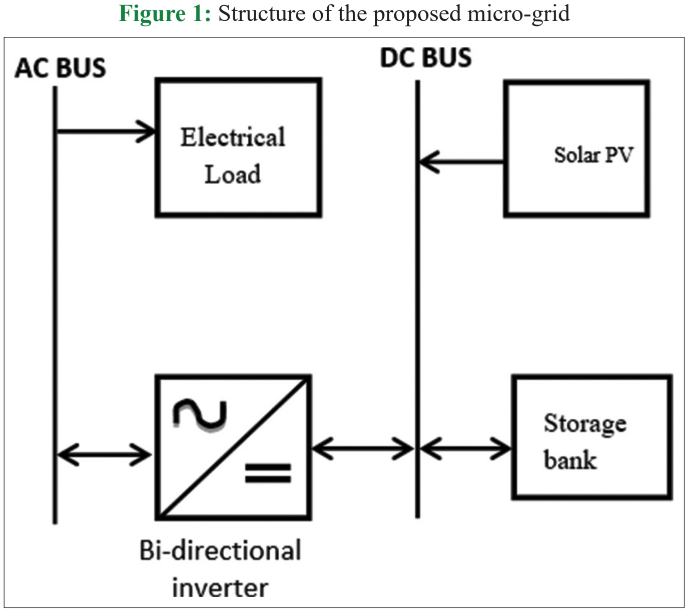
This work aims to propose a micro-grid with a renewable power system that can satisfy the electricity load of the Obayantor community by carrying out an economic and feasibility study. The following steps were taken (i) economics and technical analysis of the existing Solar-PV electricity. (ii) Evaluation of the diesel-only electricity system and finding out the best optimal system.

2. METHODOLOGY

Most microgrid project in rural electrification studies fail as revealed in the literature due to low renewable energy systems (RESs) utilization and detailed technical-economic analysis before designing a dependable power system, especially in developing countries. Evaluation of the system economics helps to establish the various costs involved in micro-grid power projects. The cost includes the initial capital, operation, and maintenance costs, and cost of energy (COE).

To attract potential investors into energy projects, the power system's technical feasibility and financial viability assessment is needed to have a successful commercial application and implementation. Especially for rural electrification. Technical feasibility is essential because it helps to provide continuous access to electricity. At the same time, the financial viability assessment is vital to make the energy affordable for the community and encourage potential investors, including energy decision planners. The proposed microgrid structure is given in Figure 1, comprising of Solar PV, battery, and bi-directional Converter.

Figure 1: Structure of the proposed micro-grid



2.1. Assessment of the Area of Study

The Obayantor community in Benin City is situated in Edo state, in the Southern part of Nigeria, with an 862 km^2 approximate area. The rural community does not have high energy consumption like the urban area. The appliances commonly used include domestic appliances such as fans lighting, and fridges. The Solar microgrid has solar modules of 300 W, 65 kW diesel generator

The microgrid consists of 300 W solar PV modules, a diesel generator of 65 kW, a battery backup system, a charge controller, a bi-directional converter system. The micro-grid structure is as shown in Figure 1. The community aerial view is given in Figure 2,

2.2. Load Assessment

The field research method used was quantitative analysis, which involved analyzing data gathered from interviews and questionnaires administered to the community members. The operation hours of the users' electrical loads decide the entire communities' energy utilization and load profile. The appliances operating time and the amount of energy consumption vary from one house to another. Visiting different remote homes allowed the author to ascertain the common appliances used by energy users. The data makes the 24-h analysis possible in this work. Most of the dwellers are not available in the afternoon. The power consumption is higher in the morning and evening times than in the afternoon Figure 3.

2.3. Resources Assessment

Solar energy is the energy source used in the off-grid power system under study in Obayantor, Nigeria. The hourly solar irradiance information serves as an input to the simulation software model (Al-falahi et al., 2017). A constant reduction in Photovoltaic solar prices over the years has increased the installed PV capacity worldwide. Solar radiation in the area with latitude: 6° 20' 21.0660'' N, longitude: 5° 37' 2.8092'' E co-ordinate is 4.35 kWh/m^2/day as given in Figure 4 from the NASA data site (NASA, 2020).

2.4. Micro-grid Component

2.4.1. Solar PV

The power output of the Solar-PV system is based on the rated capacity, de-rating factor, and irradiance as in equation 1-2 (Kharrich et al., 2019) (Esan et al., 2019):

Figure 2: Obayantor community aerial view

Figure 3: Community hourly load demand profile

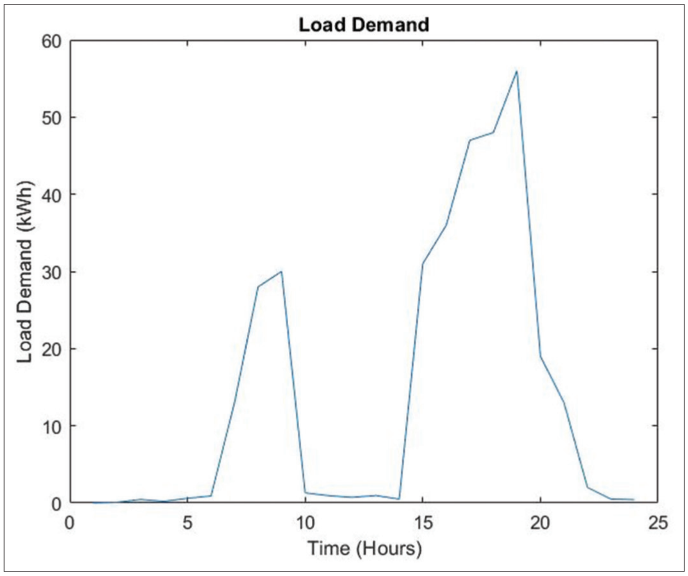
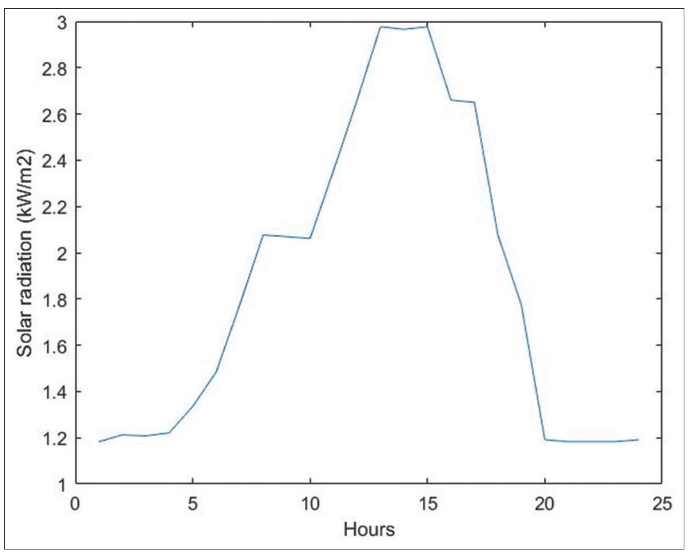


Figure 4: Solar radiation



$$P_{pv} = P_r f\left(\frac{H_T}{H_{T,STC}}\right)[1+\alpha_p(T_c - T_{c,STC})] \quad (1)$$

$$T_c = T_{amb} + \left(\frac{NOCT - 20^o}{800}\right) xG \quad (2)$$

Tc was computed using equation (2). The Tc value of a PV module is when the ambient temperature is 20°C.

Where: P_{pv} =PV output power, P_r = capacity rating of the PV module under standard test conditions in kW, f = PV de-rating factor, H_T = solar irradiation incident of the location on the PV array (kW/m²), $H_{T,STC}$ = incident irradiation at standard test conditions (1 kW/m²), α_p = temperature coefficient of power (°C) for the selected module, T_c= PV cell temperature (°C), $T_{c,STC}$ = PV cell temperature under standard test conditions.(25°C), T_{amb} =Ambient temperature (°C), Noct =Norminal cell temperatute, (°C) usually in manufacturer's datasheet.

2.4.2. Diesel generator (DG)

A diesel generator was utilized to smoothly meet the electrical power demand as a backup source whenever the Solar PV is absent. The fuel (diesel) consumption rate Q_t (*t*) is obtained by using equation (3) (Kharrich et al., 2019) (Aderibigbe et al., 2017):

$$Q_t(t) = \alpha_{DG} P(t)_{DG,gen} + \beta_{DG} P_{DG,rat} \quad (3)$$

Where: $Q_t(t)$=consumption rate of diesel (l/kWh), $P(t)_{DG,gen}$ =Power output Generated (kW), $P_{DG,rat}$ = Diesel generator rating (kW), α_{DG} = fuel consumption coefficient i.e. generator fuel curve slope typically 0.246 l/kWh (Mohamed et al., 2016), β_{DG} = fuel consumption coefficient i.e. fuel curve intercept coefficient (typically 0.08145 l/kWh (Mohamed et al., 2016).

2.4.3. Batteries

A battery energy storage system was used as a backup to supply power when the renewable energy source generator is not supplying. eq (4) gives the battery system size (A-h) (Alzahrani et al., 2017) (Elizabeth et al., 2019).

$$Bsize = \frac{E_{load} \times Days_{off}}{DoD_{max} \times \eta_b \times \eta_{inv}} \quad (4)$$

Where: E_{load} is the demand for the community which must be satisfied. $Days_{off}$, is the number of days the battery will run (usually 3-5 days). η_{inv}, is the inverter efficiency, 92%, η_b, is the efficiency of battery 95%, DoD_{max} is the depth of discharge of the battery system (usually 50-80% standard for deep cycle batteries).

3. TECHNICAL-COST PARAMETERS

The economic performance of the isolated microgrid was evaluated using the economic mathematical models in Equations 5-15 in MATLAB 2018a code.

3.1. Cost of Electricity

The cost of electricity is the primary part applied in technical and economic research. It calculates the unit cost of energy generated and the overall energy that can be produced during the project lifetime. The unit price of electricity was presented in equation (5) (Kuznetsov et al., 2019).

$$COE\left(\frac{\$}{kWh}\right) = \frac{\text{Total Net Present Cost}(\$)}{P_{L(kW)} * (8760h / year)} COE \quad (5)$$

Each model was calculated by using parameters listed in Table 1.

3.2. Net Present Cost

$$NPC = C_{cap.} + C_{rp}. + C_{O\&M} \quad (6)$$

Where:

$C_{cap.}$ = initial Capital cost

C_{rp}. = Replacement cost

$C_{O\&M}$= Operation & Maintenance cosF

Equation (6) (Mehrpooya et al., 2018) estimated the existing micro-grid system's NPC.

Table 1: The operational cost value of system components parameters

Name of Components	Capital Cost	Replacement Cost	O&M Cost/ Year
Solar PV (W)	3400 ($/KW)	3400 ($/KW)	10 ($/yr.)
Diesel generator/Kw	5479 ($)	5479 ($)	0.0273 ($/hr.)
Battery kWh	270 ($/unit)	240 ($/unit)	10($/yr)
Bi- directional converter/KW	350($/kW)	350($/kW)	10($/kW/yr.)

3.3. Financial Assumptions

The paper used inflation and interest rates of 8% and 12%, respectively. Inflation rate (f) and nominal discount rate (*i'*) were used to determine the real discount rate (*i*) according to Trading Economics' report (Tradingeconomics, 2019). 1USD is equivalent to N365 in Nigeria, as at the time of this report.

3.4. Annual System Cost (ASC)

ASC is the sum of the Annual Capital Cost (ACC), Replacement Cost (ARC), and Maintenance Cost, respectively, and the sum is multiplied by the capital recovery factor (CRF), mathematically represented in eqs. (7) – (9) (Fodhil et al., 2019).

$$ASC = (\sum_{I=1}^{N}(ACC + AOMC + ARC))xCRF(i, z) \quad (7)$$

$$C_{NPC} = \frac{ASC}{CRF(i, Z)} \quad (8)$$

$$ASC = NPC_{Tot} \times CRF \quad (9)$$

3.5. Annual Capital Cost

The cost of different components in the micro-grid system are presented using the capital cost per kW (Nejabatkhah, 2018). ACC is expressed as in equation (10) (Nejabatkhah, 2018):

$$ACC = C_{cap}\sum_{i=1}^{N}[SPV + BATT + CON + DiG] \text{ X } CRF\left(i,\ z\right) \quad (10)$$

The Capital Recovery Factor (CRF) for each component of a micro-grid is given in equation (11)

$$CRF\left(i,\ z\right) = \frac{i\,x(1+i)^{z}}{(1+i)^{z}-1} \quad (11)$$

The annual real rate of interest (%)

$$i = \frac{i' - f}{1 - f} \quad (12)$$

3.6. Annual Replacement Cost

The annual replacement cost (ARC) is the component replacement cost during the project lifetime. (Fodhil et al., 2019). The ARC was estimated in equation (13).

$$ARC = C_{repbatt} \times SFF\ (i, y_{rep}) \quad (13)$$

$C_{repbatt}$ is the cost of replacing the storage banks in US$, y_{rep} is the storage bank's lifetime within a year. SFF is the Sinking Fund Factor, calculated as shown in equation (14).

$$SFF = \frac{I}{(1+i)^{yrep} - 1} \quad (14)$$

3.7. Annual Operation and Maintenance Cost

The annualized maintenance cost (AOMC) of a microgrid power system can be calculated considering the annual inflation rate (Adefarati and Bansal, 2019). The operation maintenance cost calculations used the parameters shown in Table 1.

The annual operation and maintenance cost of the system was evaluated using equation (15) (Javed et al., 2019)

$$AMC = AOM\ (1)\ (1+f)^{y}\ [SPV + BATT + CON + DiG] \quad (15)$$

Where:
AOM (1) is the maintenance cost of each component for the first year of the project.
f = inflation rate (%), *i'* = nominal interest rate (*i'*), C_{ic} = initial capital cost
Z = project lifetime, ($), C_{cap} is the capital cost of each component.

3.8. Micro-grid Evaluation using Capacity Factor

The interest in capacity factor (CF) analysis of an HPMS is that the study provides an intelligent, summarized indication about the combined interaction between the microgrid and the site. The accurate microgrid capacity reduces the need for balancing energy and reserve power.

3.8.1. Capacity factor

Capacity factor (CF) is the ratio of actual energy produced to the maximum possible power that could have been made during a given period. The CF is expressed in equation (16)

$$CF = \frac{Actual\ energy\ produce}{\text{maximum plant rating*time duration}} \quad (16)$$

3.8.2. Simple payback period

Simple payback (SPBP) is an economic index for measuring generation plants to consider the time-dependent valuation of the electrical power to determine the optimal design better than COE.

$$SPBP = \frac{C_{ic}}{A_{AR}} \quad (17)$$

A_{AR} is calculated from equation (18)

$$A_{AR} = CF \times T \times P_{ratedx}\ x\ COE \quad (18)$$

ROI

Where: C_{ic}= Initial capital cost, A_{AR}= Average annual revenue based on hourly production.
CF= Capacity factor, T= Time in hours, P_{rated}= Rated power of Solar PV.

3.8.3. Return on investment

The rate of investment (ROI) is just the inverse of a simple payback period. Unlike SPBP, ROI is usually expressed in percentage as seen in equation (19).

$$\text{ROI} = \frac{A_{AR}}{C_{ic}} * 100 \quad (19)$$

3.8.4. Net present value

The initial capital cost C_{ic} is the present cost value of the micro-grid power production, assuming the production to be constant annually from year to year. Then the uniform cash flow must be discounted as it occurs in the future. NPV is calculated, as shown by equation (20) (Muyiwa et al., 2017).

$$\text{NPV} = A_{AR} * \left[\frac{(1+i)^Z - 1}{i*(1+i)^Z} \right] - C_{ic} \quad (20)$$

4. RESULTS AND DISCUSSION

The optimization process in MATLAB simulated a range of equipment options over varying constraints depending on the Annual system cost (ASC). The combination of system components is arranged from the most effective cost to the least effective cost.

The result for capital cost, Net present cost, and ASC of the solar PV cost was higher than the result for the diesel generator, which is an indication that the initial cost of solar is always more expensive (Abdilahi et al., 2014). The diesel's annual energy production and capacity factor were higher than that of the solar, indicating that the diesel generator performs very close to the rated capacity. The NPV was positive and high, which is proved in (Richard et al., 2020), suggesting that solar PV has better present investment worthiness over the project's lifespan. The diesel-based micro-grid has a shorter SPBP of 1.5yrs, considering the payback period because of its lifetime of 20000 hours, which is approximately two years, meaning the micro-grid owners will get back the money invested within a short period. Still, the energy source will not function for an extended period, unlike the solar with an SPBP of approximately nine years and the lifetime of solar being twenty-five years. The cost of diesel energy is \$0.3, which is higher than that of solar of \$0.10. Hence solar micro-grid could be chosen primarily for a remote location with low-income earners and affordable, thereby making their energy consumption cost lower. But the diesel micro-grid has higher annual energy production, which can be very useful in areas where solar irradiance is low. Also, the rate of return on investment of project for the solar microgrid is seen to be lower, 33%, than that of the diesel microgrid of 67%, indicating that the energy planner will get back their capital invested on a diesel micro-grid within a short period because of the diesel operating hours than the solar microgrid.

These results coincide with the results (Abdilahi et al., 2014) and (Tsuanyo et al., 2015). Tsuanyo et al. 2015 reported that the COE and NPC of the stand-alone diesel generators were higher than the Hybrid Solar PV/battery but increased the cost of investment in the solar system components. The economic evaluation was conducted, assuming that the microgrid is also supplied by another energy source, including a diesel generator Table 2.

Figure 5 showed that the solar microgrid's capital cost and net present value had the highest share in all the economic value than the diesel generator. The work showed that renewable energy sources have higher capital costs while the diesel generator alone has lower capital costs. The result is comparable with other literature works (Tsuanyo et al., 2015). Also, the diesel microgrid showed a higher cost of energy and ROR than that of the Solar PV. It was also seen that the Solar PV microgrid had a higher percentage of SPBP. For a microgrid with this energy resource type, the diesel will have less impact on the system economy but with a higher SPBP rate, but might not be considered the best option for an energy source because of its environmental impact. The solar microgrid produced less green gas, as reported in the literature (Hafez and Bhattacharya, 2012). Hafez and Bhattacharya 2012, in their work, noted that renewable micro-grid reduced emissions of CO_2 significantly compared to conventional energy resources.

Table 2: Economy of existing microgrid

Item	Solar PV system	Diesel Generator
Capital cost (\$)	227,957.41	58,954.04
Capacity factor	0.57	0.69
Net present cost (\$)	37,085.30	32,020
Cost of energy (\$)	0.10	0.3
ASC (\$)	290,865.08	59,517.9
Simple bay back period (years)	3	1.5
Rate of return (%)	0.33	0.67
Net present value (\$)	476,952.6	8,948.92
Annual energy production (kWh)	210240	175200

Figure 5: Generating sources cost compared

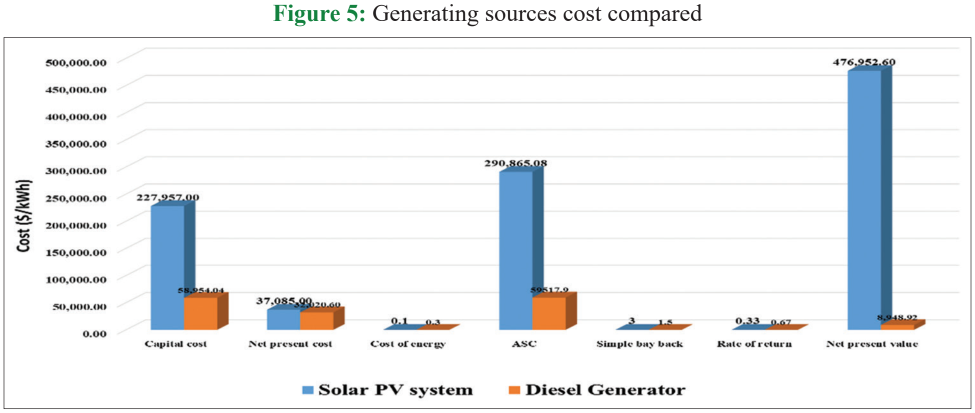


Figure 6: Energy cost compared

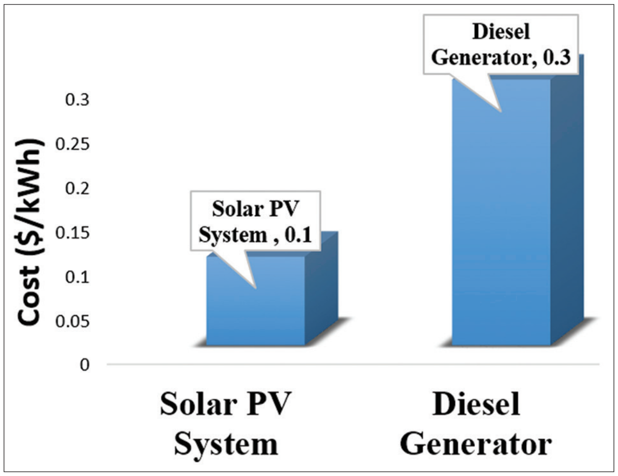


Figure 6 presents the cost of energy for each energy source. The values are 0.10 and 0.3 USD/kWh, which are competitive with the energy market electricity price (0.12-0.24 USD/kWh). However, the energy price of diesel was higher than that of Solar PV, indicating that the existing micro-grid is economically viable compared to a diesel-only microgrid.

4. CONCLUSIONS

A techno-economic study of microgrid systems and the existing base case has been executed with certain assumptions. The area considered in this study was the Obayantor community in Nigeria, using the MATLAB tool.

The study investigated some economic indicators: net present cost, annual system cost, cost of electricity generated, simple payback period, rate of return, net present value, and compare the existing power system with a diesel micro-grid in terms of cost. The result gave an extensive range of differences between the solar PV microgrid and the diesel microgrid system taking the project lifetime to be 25 years. The results showed that the diesel-alone microgrid system is 4.71 times and 0.2 times more costly than the solar-based microgrid system in terms of energy and ASC costs, respectively, primarily due to the present increasing diesel fuel rate.

This study will further motivate investors to know the technical and economic prospects of a solar PV -based microgrid power system. The study also illustrates the serious drivers for proposing and implementing such an energy system in any rural community with zero grid connection. The policymakers could take a clue from this study. Further studies would include other renewable energy sources, like wind and biomass, for cleaner energy generation.

5. ACKNOWLEDGMENTS

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