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Optimal Sizing of a Sustainable and Climate Resilient Microgrid System

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Abstract: The research investigates the potential of an off-grid microgrid system powered by renewable energy sources in Barangay Ransang, a remote village in Palawan. The study aims to determine the renewable energy potential, identify the most economical combination of renewable energy sources, and evaluate the financial benefits of the proposed system. The researchers used HOMER software to simulate and optimize the microgrid system, identifying a 2.0 MWp solar PV array, 0.840 MW diesel generators, and a 1.0 MWh battery energy storage system as the optimal solution. This configuration provides 40% renewable fraction and a cost of energy of $0.287/kWh. The Simplified Planning Tool (SPT) validated the results, confirming the feasibility of the proposed microgrid system. The hybrid power plant's levelized cost of electricity (LCOE) is $0.287/kWh, significantly cost-saving compared to a diesel-only system with an LCOE of $0.424/kWh. Implementing this off-grid microgrid system in Barangay Ransang is projected to result in annual savings of $578,219.10 in Universal Charge on Missionary Electrification (UCME) subsidy, further contributing to the project's economic viability. The findings can serve as a reference for other off-grid electrification projects in the Philippines and beyond, offering potential benefits to remote areas waiting to be electrified.

Keywords: Microgrid system, Optimal sizing, Renewable energy, Hybrid system, Village electrification

Introduction

Barangay Ransang in the Municipality of Rizal is one of the un-electrified villages in the Province of Palawan. It is approximately 230 kilometers from the City of Puerto Princesa and more than 10 kilometers from the town proper of Rizal. Due to its location, the line connection to the existing distribution line is costly and technically impractical. One possible solution for the electrification of Barangay Ransang is the use of off-grid microgrid technology utilizing renewable energy sources. An off-grid microgrid is a standalone system that is not connected to the main grid of electricity. With this technology, the barangay will have its own power generation facility and distribution system to provide electricity within the area. The lack of continuous, affordable, clean, and reliable electricity supply in village affects the residents' living conditions, preventing them from improving their healthcare, education, and livelihood.

Objectives of the Study

The study aims to determine the viability of installing an off-grid microgrid system utilizing renewable energy sources in Barangay Ransang. The specific objectives of the study are the following:

1. Determine the renewable energy potential of the area.
2. Determine the most economical combination of renewable energy sources for the microgrid system.
3. Determine the financial benefits of the system.

This study is important to ensure a continuous supply of electricity in a clean and reliable manner at an affordable price for the residents. This can also be a reference for other off-grid electrification projects in the country. There are still a lot of remote areas waiting to be electrified, and this study can help the stakeholders in rural electrification conduct their feasibility studies. Distribution line design for the microgrid system is not part of this study. Same with the design of the power generation facility. This study will only determine the most viable renewable energy configuration for the power plant considering its techno-economical aspects. Sizing of the solar PV, diesel generator, and battery backup system is included in the study.

Review of Related Literature

In recent years, the investigation of off-grid hybrid renewable power systems has attracted significant attention from researchers worldwide Brijesh et al. (2019) conducted a study using microgrid for sustainable development of remote villages. Babayomi et al. (2020) presented the importance of energy efficiency for sustainable renewable microgrids for off-grid electrification. Singh Dhawan and Tamrakar (2022) studied the potential of standalone microgrids as a sustainable option for energy handling. Furthermore, Kumar et al., 2018) suggested a novel methodological framework for the design of a sustainable rural microgrid for developing nations. While Zaman and Razzak (2022) accomplished a sustainable microgrid analysis for Kutubdia Island of Bangladesh.

Researchers further explored the use of microgrid system utilizing different combination of technologies for various applications. Keskamol and Hoonchareon (2015) studied the sizing of battery energy storage system for sustainable energy in a remote area. Habib et al. (2019) accomplished a PV-Wind-Battery based standalone microgrid system with MPPT, (Zaman and Ongsakul, 2022) introduced a hybrid microgrid optimization for smart city planning on Saint Martin's Island in Bangladesh. Mukhopadhyay and Ray (2021) conducted a techno-economic-environment analysis of solar PV smart microgrid for sustainable rural electrification in agriculture community. Bandyopadhyay et al. (2020) also made a techno-economical model based optimal sizing of PV-Battery systems for microgrids. It is evident in the previous researches the importance of a techno-economical analysis in ensuring the optimal and sustainable design of a microgrid system. Santos et al. (2021) presented an integrated optimal sizing and dispatch strategy for microgrids using HOMER Pro. Popescu (2021) also utilized HOMER Pro software in conducting a techno-economic analysis for renewable energy microgrid systems. Islam et al. (2021) optimized a microgrid system for community electrification by using HOMER Pro, similar to Baral et al. (2022) in the design and economic optimization of community load based microgrid system.

Missionary Electrification in the Philippines

The 2030 Agenda for Sustainable Development was adopted by the United Nations Member States in 2015, with 17 Sustainable Development Goals (SDGs) to urge all countries to achieve a more sustainable future for all. Considered crucial to the achievement of most of these goals is SDG 7 - affordable and clean energy access. Energy access is defined as access to electricity and modern cooking, with electricity access considered to be fundamental to poverty eradication, improved health, quality education, economic growth, and inclusive sustainable development. The Philippines aims to achieve 100% electrification at household level in the next few years and the Department of Energy (DOE) has reported that as of December 2016, household electrification rate for the entire country is at 90.65%. The Philippine electrification system is categorized into on-grid and off-grid, where on-grid areas are connected or served by the main transmission backbone of Luzon, Visayas, and Mindanao, serviced by the National Grid Corporation of the Philippines (NGCP); and off-grid areas are electrified by the National Power Corporation Small Power Utilities Group (NPC-SPUG).

Republic Act No. 9136, otherwise known as the Electric Power Industry Reform Act or EPIRA, was enacted in 2001 as overarching legislation to manage electrification in the country and to transition to cleaner sources of energy. Pursuant to Sec. 2 (a) of EPIRA, the government stipulates the acceleration of total electrification of the country. With this declaration, the NPC-SPUG or its successors-in-interest, distribution utilities (DUs) concerned, and/or qualified third parties (QTPs) are mandated to provide missionary electrification to off-grid areas in the country that are unserved or underserved in terms of electricity access. DOE, through its Implementing Rules and Regulations (IRR) of EPIRA, defines missionary electrification as the provision of basic electricity service in unviable areas or areas within the mandated franchise area of a DU where the extension of the distribution line is not feasible. Missionary electrification has the ultimate goal of bringing the operation in these areas to an acceptable level. By its definition, missionary electrification covers all off-grid areas in the country.

Through DOE's 2016-2030 Philippine Energy Plan, three programs are identified to support off-grid electrification efforts in order to achieve 100% household electrification: (a) household Electrification Program (HEP), which aims to accelerate renewable energy adoption with the use of mature renewable energy technologies (RETs) such as solar photovoltaics (PV) to provide electricity access to off-grid households; (b) mainstreaming of Solar PV through the Access to Sustainable Energy Program (ASEP), where DUs are encouraged to implement solar home systems (SHS) to dispersed households in remote areas; and (c) Qualified Third Party (QTP) Program, allowing qualified third parties to provide electricity access to areas deemed unviable and waived by the DUs. A more recent development in 2022 is the passing of the Philippine Microgrid Systems Act accelerating the development of microgrid systems for rural electrification in the country.

Methodology

A software called HOMER (Hybrid Optimization of Multiple Energy Resources) was used for system optimization. This software is an internationally accepted tool in the simulation of microgrid systems. The techno-economic analysis was conducted using this tool. Simulation results were analyzed, and the most viable power system configuration was recommended. Figure 1 below shows the conceptual framework for the study.

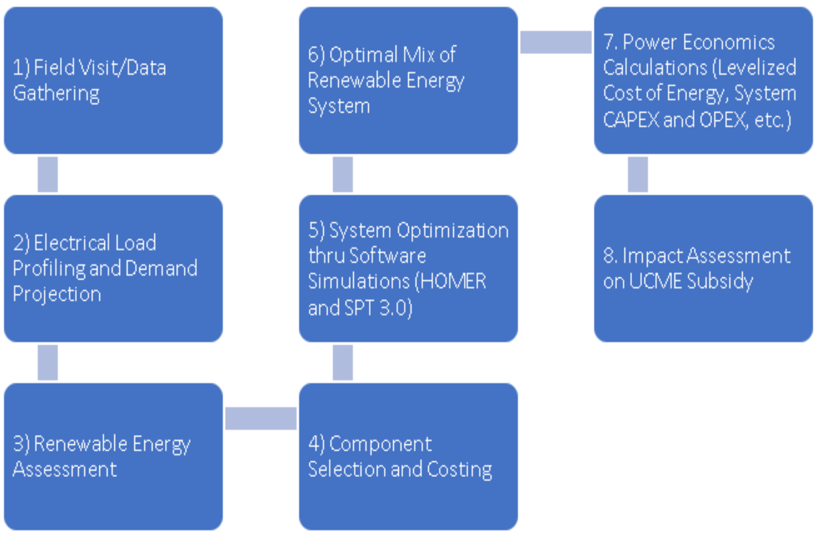

Figure 1. Conceptual framework of the study

The conceptual framework includes the following activities (1) data gathering and actual field surveys to gather not only granular technical and operational/financial data but also get the insights and suggestions of stakeholders (2) electrical load profiling and demand projections to determine the energy consumption of the study area (3) renewable energy assessment to identify the available renewable energy resources for power generation (4) component selection and costing as a major input in system optimization (5) determination of the optimal renewable energy supply mix for the study area by using two different tools a) HOMER Software and b) an Excel-based tool called Simplified Planning Tool (SPT) 3.0 for comparison of results (6) analysis of the calculated optimal supply mix (7) power economics calculations to determine the financial viability of the system, and (8) assessment on the impact of sustainable microgrid to the use of Universal Charge on Missionary Electrification (UCME) subsidy. EPIRA prescribed UCME imposable to all-electric consumers nationwide.

The UCME established the provision of subsidies in areas under missionary electrification so that development and progress could also happen in these areas similar to grid-connected communities. End users under missionary electrification are only required to pay the Subsidized Approved Generation Rate (SAGR) plus any ERC-approved cost adjustments notwithstanding the higher True Cost Generation Rate (TCGR) of these areas. The difference between TCGR and SAGR is claimed from the UCME Subsidy.

HOMER Simulation

Load profile preparation and renewable energy assessment were done before the HOMER simulation. A detailed evaluation of the electrical load demand of the community and available solar energy resources was separately conducted. This is carried out outside the software, and data is fed for the simulation. The electrical load profile and demand projection for Barangay Ransang were gathered thru an electrical load survey. HOMER first runs an hourly simulation of all possible configurations on different system types. The speed of simulation processing allows for the evaluation of thousands of combinations. This hourly simulation also provides improved accuracy over statistical models that typically evaluate the average monthly performance of a system. The modeling process done by the software involves two key stages: i) technical feasibility; and ii) comparison of life cycle costs. HOMER first tests the capability of each proposed configuration to serve the electric loads in the power grid within a set of constraints set by the modeler. Once the electrical demand is addressed, HOMER calculates the lifecycle cost of the system for each configuration using user-defined factors, such as the load size, reliability requirements, and resource quality. The lifecycle cost or the levelized cost of electricity (LCOE) is computed using the discounted cash flow method, i.e., the net present value of all the costs of installing (CAPEX) and operating (OPEX) the system over the project life.

During HOMER simulations, the projected demand will be subjected to random variabilities to add randomness to the load data to make it more realistic. These random variabilities are day-to-day variability and timestep variability. After the simulation process, the software sorts the feasible results in order of increasing net present value (NPV). This cost is the present value of the capital cost, component replacement, operation and maintenance cost, and fuel costs. The software lists the optimal system configuration for each system type, defined as the one with the least net present value. The goal of the optimization process is to identify the optimal value of each variable. The possible decision variables in the study are the following:

1. The capacity of the solar PV
2. The capacity of the diesel generator sets
3. The capacity of the battery energy storage system
4. The control or applicable system dispatch

The sensitivity analysis in the software then repeats this optimization using user-defined factors, such as diesel fuel price, electrical demand, system reliability requirement, and resource quality.

Software Inputs

Tables 1 to 3 show the technical and financial inputs for the HOMER simulation. These values are based on the actual costs and technical specifications of equipment identified for the project. Cost inputs are not only referring to the equipment itself but also include the cost of the balance of the system to have a complete operational system.

Table 1. Solar PV inputs

Item	Unit	Value
530 Wp, Monocrystalline, Half-cell Module		
Capital cost per kW	$	1,100
Replacement cost per kW	$	1,000
O&M cost per kW	$/year	35
Lifetime	years	25
Derating factor	%	84.8

The replacement cost is lower than the capital cost because some of the system components, like mounting structures, cables, etc., can still be used after the replacement of solar panels. This is also applicable to the replacement cost for diesel generators, batteries, and bi-directional inverter. The minimum load ratio of the diesel generators is at 40% to maintain the good value of specific fuel oil consumption (SFOC). An annual increase of two (2) percent in fuel price is included in the simulation to determine the impact of increasing fuel price on the optimal configuration of the hybrid power plant.

Table 2. Diesel generator inputs

Item	Unit	Value
235 kVA (standby rating), silent type, 60 Hz, 1,800 RPM, 3 Phase, 400 Volts		
Capacity (prime rating)	kW	168
Capital cost per unit	$	40,000
Replacement cost per unit	$	30,000
O&M cost per unit	$/RH	2
Fuel price	$/L	0.9
Minimum load ratio	%	40
Lifetime	hrs	15,000
Minimum Runtime	minutes	60
Fuel curve		
100% loading	L/hr	44
75% loading	L/hr	33
50% loading	L/hr	23
25% loading	L/hr	14

Table 3. Battery inputs

Item	Unit	Value
Lithium Iron Phosphate (LFP), 0.5 C-rate		
Capital cost per MWh	$	700,000
Replacement cost per MWh	$	650,000
O&M cost per MWh	$/year	5,000
Lifetime	years	15
Throughput	kWh	3,000,000
Voltage	V	768
Minimum State of Charge	%	10

Load Profile

Table 4. Projected load profile

	Demand (kW)											
Time	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
0	407	527	376	470	537	525	389	373	445	482	348	459
1	398	515	368	460	524	513	380	364	435	471	340	448
2	389	503	359	449	512	502	371	356	425	460	332	438
3	380	491	351	438	500	490	362	347	414	449	325	427
4	366	473	338	422	482	472	349	335	399	433	313	412
5	370	479	342	428	488	478	354	339	404	438	317	417
6	338	437	312	390	445	436	323	309	369	400	289	380
7	236	305	218	273	311	304	225	216	258	280	202	266
8	232	299	214	267	305	299	221	212	253	274	198	261
9	273	353	252	315	360	352	261	250	298	323	234	307
10	292	377	269	337	384	376	278	267	318	345	249	328
11	296	383	274	342	390	382	283	271	323	351	253	334
12	296	383	274	342	390	382	283	271	323	351	253	334
13	292	377	269	337	384	376	278	267	318	345	249	328
14	287	371	265	331	378	370	274	263	313	340	245	323
15	287	371	265	331	378	370	274	263	313	340	245	323
16	292	377	269	337	384	376	278	267	318	345	249	328
17	296	383	274	342	390	382	283	271	323	351	253	334
18	324	419	299	374	427	418	309	296	354	384	277	365
19	435	562	402	502	573	561	415	398	475	515	372	490
20	449	580	415	518	591	579	429	411	490	532	384	505
21	463	598	428	534	610	597	442	424	505	548	396	521
22	458	592	423	529	604	591	438	419	500	543	392	516
23	435	562	402	502	573	561	415	398	475	515	372	490

Table 4 presents the projected hourly load profile of the community considering the seasonality of demand in the area. Random variabilities are added to these values during the HOMER simulation to reflect the actual situation at the site. A 2.5 percent annual increase in demand is considered in the simulation to determine the effect of demand increase in the operation of the hybrid power plant.

Solar Resource

The monthly average solar global horizontal irradiance data used in the simulation is from the database of NASA. The annual average data for the site is 5.68 kWh/m^2/day. The monthly values are presented in Table 5.

Table 5. Daily radiation and clearness index

Month	Clearness Index	Daily Radiation (kWh m^2/day)
January	0.554	5.28
February	0.567	5.69
March	0.595	6.2
April	0.626	6.5
May	0.596	5.99
June	0.549	5.38
July	0.553	5.46
August	0.555	5.65
September	0.57	5.89
October	0.542	5.47
November	0.561	5.39
December	0.56	5.23

The clearness index is a measure of the clearness of the atmosphere. It is the fraction of the solar radiation transmitted through the atmosphere to strike the surface of the Earth. It is a dimensionless number between 0 and 1, defined as the surface radiation divided by the extraterrestrial radiation. The clearness index has a high value under clear, sunny conditions and a low value under cloudy conditions.

Results and Discussions

Based on the techno-economic analysis using HOMER software, a system with a capacity of 2.0 MWp solar PV, 0.840 MW (5 x 168 kW) diesel generators, and 1.0 MWh BESS is capable of supplying the demand at a renewable fraction of 40%, as shown in Table 6. All system configurations are in load following dispatch strategy.

Table 6. Simulation results

Solar PV (kW)	DG1 (kW)	DG2 (kW)	DG3 (kW)	DG4 (kW)	DG5 (kW)	DG6 (kW)	BESS (MWh)	COE ($/kWh)	RE Frac (%)
2000	168	168	168	168	168		1	0.287	40
2000	168	168	168	168	168	168	1	0.289	40
2200	168	168	168	168	168		1	0.291	41
2200	168	168	168	168	168	168	1	0.293	41
2400	168	168	168	168	168		1	0.295	42
2400	168	168	168	168	168	168	1	0.298	42

The resulting cost of energy for the selected system is $0.287 per kWh. The cost of energy is the true cost of generation rate that the electric consumers will pay for electricity use. To validate the results, another tool was used using the same technical and financial inputs. Table 7 shows the simulation results from the Simplified Planning Tool (SPT). The Reiner Lemoine Institute (RLI), under the EU ASEP technical assistance, has developed SPT for simulating typical off-grid power supply configurations. The tool allows for least-cost analytical assessments based on the levelized cost of electricity, similar to HOMER software.

The results are not exactly the same as HOMER, but the values are close enough to validate the results. Table 8 shows the cost summary in net present value from HOMER. Solar PV has the highest capital cost, but diesel generators will have the highest net present value due to their high fuel expenses.

Table 7. Simulation results from SPT

Parameter	Value	Unit
Load consumption (+losses)	4,220,577.40	kWh/year
System installed PV capacity	2,000.00	kW
Installed battery capacity	1,000.00	kWh
Installed diesel capacity	840	kW
PV output	2,971,100.00	kWh/year
Battery output	659,531.50	kWh/year
Diesel generator output	2,455,260.90	kWh/year
Fuel consumption	614,372.20	liter/year
LCOE	13.06	PHP/kWh
RE-share	41%	in percent
Unmet load	0	kWh/year

Table 8. Cost summary of the system

Cost Summary (Net Present)	System	Solar PV	DG	Batteries	Bi-directional Inverter
Capital	$3,190,000	$2,200,000	$200,000	$700,000	$90,000
Replacement	$913,103	$0.00	$241,946	$637,279	$33,878
O&M	$1,194,482	$810,619	$297,011	$57,901	$28,951
Fuel	$5,050,630	$0.00	$5,050,630	$0.00	$0.00
Salvage	($289,324)	($127,523)	($18,185)	($143,616)	$0.00
Total	$10,058,891	$2,883,096	$5,771,402	$1,251,565	$152,829

Table 9. DG operation parameters

Description	Unit	DG 1	DG 2	DG 3	DG 4	DG 5
Hours of operation	hours/yr	5,168	4,238	2,977	438	3
Number of starts	starts/yr	376	377	547	231	3
Operational life	yr	2.9	3.54	5.04	34.2	5,000
Capacity factor	%	54.7	44.3	23.9	2.52	0.0137
Fixed generation cost	$/hr	7.15	7.15	7.15	7.15	7.15
Marginal generation cost	$/kWh	0.214	0.214	0.214	0.214	0.214
Electrical production	kWh/yr	805,662	651,996	351,813	37,138	202
Mean electrical output	kW	156	154	118	84.8	67.2
Minimum electrical output	kW	67.2	67.2	67.2	67.2	67.2
Maximum electrical output	kW	168	168	168	168	67.2
Fuel consumption	L/yr	209,912	170,070	94,184	10,375	58.5
Specific fuel consumption	L/kWh	0.26	0.26	0.27	0.28	0.29
Fuel energy input	kWh/yr	2,065,536	1,673,491	926,775	102,094	576
Mean electrical efficiency	%	39	39	38	36	35

Tables 9 to 11 present the operation parameters of the hybrid power system in its first year of operation. The average battery autonomy of the upgraded system is 2.44 hours. When fully charged, the BESS can continuously supply power to the demand for up to 2.44 hours without solar PV and diesel generators. This is important when the production of solar panels is low. The storage bank autonomy is the ratio of the storage bank size to the electric load. HOMER calculates the storage bank autonomy using the following equation:

$$A_{batt} = \frac{N_{batt} V_{nom} Q_{nom} \left(1 - {q_{min}}/{100}\right)(24\, h/d)}{L_{prim,ave}(1000\, Wh/kWh)} \quad \text{(Eq. 1)}$$

With: N_{batt} :number of batteries in the storage bank, V_{nom} :nominal voltage of single storage (V), Q_{nom}:nominal capacity of single storage (Ah), q_{min}: minimum state of charge of the storage bank (%), $L_{prim,ave}$: average primary load (kWh/d)

Diesel Generator 5 is expected to operate at a very minimal time per year. This unit also serves as a contingency reserve when one of the other units will need repair or maintenance. According to the definition from the Philippine Grid Code of 2001, a contingency reserve is the generating capacity intended to take care of the loss of the largest synchronized generating unit or the power import from a single grid interconnection, whichever is larger.

Table 10. Solar PV operation parameters

Description	Value	Unit
Rated capacity	2,000	kW
Mean output	359	kW
Mean output	8,620	kWh/d
Capacity factor	18	%
Total production	3,146,231	kWh/yr
Minimum output	0	kW
Maximum output	1,667	kW
PV penetration	95.4	%
Hours of operation	4,380	hours/yr
Levelized cost	0.0791	$/kWh

In the first year of operation, around 33% of the energy produced from the solar panels is not utilized, but this value will be reduced to 18.5% on the 20th year of operation. There is excess energy because of the low demand when solar production is high. The demand in the area is primarily residential loads, with the peak happening during night time. The excess energy during the day can still be utilized for solar water pumping and other similar applications.

HOMER uses Equation 2 to calculate the output of the PV array:

$$P_{PV} = Y_{PV} f_{PV} \left(\frac{\overline{G}_T}{\overline{G}_{T,STC}} \right) \left[1 + \alpha_P \left(T_c - T_{c,STC}\right)\right] \quad \text{(Eq. 2)}$$

With: Y_{PV}: the rated capacity of the PV array, meaning its power output under standard test conditions (kW), f_{PV}: the PV derating factor (%) $\bar{G}_T$: the solar radiation incident on the PV array in the current time step (kW/m^2), $\bar{G}_{T,STC}$: the incident radiation at standard test conditions (1 kW/m^2), α_P: the temperature coefficient of power (%/°C, T_c : the PV cell temperature in the current time step (°C)

$T_{c,STC}$: the PV cell temperature under standard test conditions (25°C)

Table 11. Battery operation parameters

Description	Value	Unit
Autonomy	3.06	hr
Annual throughput	346,043	kWh/yr
Energy in	363,759	kWh/yr
Energy out	328,286	kWh/yr
Average energy cost	0	$/kWh
Battery wear cost	0.228	$/kWh
Losses	36,425	kWh/yr
Storage depletion	951	kWh/yr

The average energy cost of the battery in the table is zero. According to the definition of a hybrid system in Article 1.1, PEC Part 1, 2017 Edition: "…Energy storage systems such as batteries, flywheels, or superconducting magnetic storage equipment do not constitute a power source…". The energy cost will be attributed to the power source responsible for the charging. In this case, all energy cost is applied to the solar PV because the system dispatch is load-following. The diesel generators will never charge the batteries. With the true cost of power generation for a diesel only microgrid system at $0.424/kWh, the proposed system utilizing the available renewable energy sources will have a savings of $0.137/kWh. This is equivalent to an annual savings of $578,219.10 in UCME subsidy for the electrification of the community.

Summary and Conclusion

The lack of continuous, affordable, clean, and reliable electricity supply in Barangay Ransang affects the residents' living conditions, preventing them from improving their healthcare, education, and livelihood. This study aims to determine the viability of installing an off-grid microgrid system utilizing renewable energy sources in the village. Based on the techno-economic analysis using HOMER software, a system with a capacity of 2.0 MWp solar PV, 0.840 MW (5 x 168 kW) diesel generators, and 1.0 MWh BESS is capable of supplying the demand at a renewable fraction of 40%. All system configurations are in load following dispatch strategy.

The results were validated with another tool using the same technical and financial inputs. The Reiner Lemoine Institute (RLI), under the EU ASEP technical assistance, has developed SPT for simulating typical off-grid power supply configurations. The tool allows for least-cost analytical assessments based on the levelized cost of electricity, similar to HOMER software. An annual savings of $578,219.10 in UCME subsidy was calculated as a result of the use of renewable energy resources in the microgrid system.

Scientific Ethics Declaration

* The authors declare that the scientific ethical and legal responsibility of this article published in EPSTEM journal belongs to the authors.

Conflict of Interest

* The authors declare that they have no conflicts of interest.

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