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Comparative Analysis of Conventional Single and Hybrid Photovoltaic Solar Energy System for Off-Grid Rural Electrification

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ABSTRACT

Renewable energy sources are essential around the globe in power generation with solar photovoltaic energy system as one of the major sources. Lack of access to affordable and reliable power in rural off-grid communities affects their wellbeing in terms of economic and social activities. In Nigeria, over 60% of Nigerian rural communities are not grid connected and lack access to affordable and reliable power. Most off-grid rural communities are depending on candles, kerosene lamps, and fossil fuel generators which are often used for lighting purposes of households, public buildings, or commercial units etc. In this paper, Falde community in Arewa LGA of Kebbi State is used as a case study. It presents a generalized model using MATLAB codes/Simulink (MATLAB Function) for data analysis to calculate power and energy demand of a selected community by using population density as varying factor with an estimated number of five (5) people per household. The average energy demand and peak load for Falde community were 726.65kWh/day and 90.86kW respectively which were used in sizing system components for system configurations. The system configurations include centralized diesel generating set (DGS), centralized photovoltaic (PV) system, a hybrid combination of DGS/PV/battery, DGS/PV, PV/battery and DGS/battery system. HOMER Pro software was used for simulation and comparative analysis of six different system configurations based on cost, greenhouse gasses emissions, sensitivity analysis, and systems optimization to select the best optimized result suitable for the selected community. The best suitable solutions to electrify and improve economic activities of the selected community out of the six configurations showed that Solar PV system has the least value of NPC (₦433,823,300.00), and DGS/PV have the highest energy production of 328,500kWh/year and finally Solar PV and PV/Battery have Zero emission of greenhouse gasses. The implementation of this research work will guarantee clean and reliable power to rural off-grid communities with reduced emission of greenhouse gasses and further ease the return on investment by potential investors.

1. INTRODUCTION

Affordable and reliable electricity supply is one of the major factors of developmental growth and livelihood of any nation. As the world population is increasing, so as the energy demand. Presently, 85% out of 17% of world population with electricity deficit rate resides in Sub-Saharan Africa (SSA) and other developing Countries [1]. Most rural areas serve as the main producers of food and ready market products for domestic use which resulted in economic growth of any nation. Stable power supply can guarantee positive performance in socio-economic activities of rural areas such as home lighting, agro-processing, education, health services, and commercial activities. Therefore, investments in rural electrification is economically and socially justifiable [2].

The power generation in Nigeria with an estimated population of 300 million by 2050, and the largest economy in the African continent is by far less than demand. The economy and energy security of the Country depend on dwindling fossil fuel reserves. Yet, it has a potential of harnessing energy from various sources of renewable energy such as solar, wind, biomass, geothermal, and water with high daily solar irradiance and wind speed of 20.1MJ/m^2/day and 1.5 to 4.1ms^{-1} respectively [3]. The power generation in the country is mostly thermal and hydro with an installed capacity of existing power stations as 13,014.40MW, an available capacity of 7,851.20MW and the peak generation ever attained was 5,801.60MW on March 01, 2021, [4]. The electricity generation capacity affects the socio-economic development of the nation in both urban and rural areas due to demand increase.

To diversify the power generation, the Country has set a target of achieving 30% of its total Energy Mix (30GW) from renewable energy sources by the year 2030 tagged ''vision 30:30:30'' and vision 2060, a net Zero emission of CO_2. The set targets can be achieved through investment costs provided by the government, foreign investors, and the private sector. In preparation to achieve the set targets, the Country has launched a scheme tagged ''solar power Naija'' which is an initiative of the Federal Government that aims to provide energy access to 5 million households, or 25 million Nigerians in off-grid rural areas and underserved urban areas under the Nigeria Economic Sustainability Plan (NESP) through the provision of Solar Home Systems (SHS) and mini-grid connections. The program was launched on 9th April 2021 with the deployment of 100,000 Solar Home Systems across the Country [5].

Renewable Energy Sources are essentially useful for sustainable and clean energy power supply and could be derived from Solar, Wind, Hydro, Biomass, Geothermal, oceans, etc. Among various renewable sources, solar energy is the most popular and substantial, and ecologically friendly. The best way to produce solar energy is by using photovoltaic (PV) technology [6]. It is a fact that lack of clean and reliable power supply affects the country's economy. The introduction of solar hybrid system in the country burst the business with an opportunity to reduce operating cost and defecting from grid [7].

Research reveals that over 60% of Nigerian rural communities are not grid connected and lack access to affordable and reliable power [8]. Most off-grid rural communities are depending on candles, kerosene lamps, and fossil fuel generators which are often used for lighting purposes of households, public buildings, or commercial units etc [9]. This research work focuses on an alternative way in providing a clean, affordable, user-friendly, and cost-effective electricity solution for off-grid rural communities through a centralized source or hybrid system that serves as a substitute for highly polluting self-generated power.

The present situation of most off-grid rural communities that are using individual petrol generators can be resolved using a centralized system that consists of a centralized generating set, solar PV-system, or a hybrid system that combine various energy resources such as diesel generating set and solar PV with or without an energy storage system that are used to meet the electricity load demand of an off-grid community. Besides socio-economic advantage, PV systems also have positive effects on public's health and their environment due to the decrease in greenhouse gasses emission [10].

The aim of the study is to carry out a comparative study of various system configurations of sustainable, cost-effective, and affordable source of power for households and public service applications to off-grid rural community.

There had been several research carried on comparative analysis of various configurations to identify suitable technology for electrification of off-grid rural community. In [11], they found out that a DC solution for off grid homes was more suitable than AC solution. They used 48V DC as system voltage, battery bank and consumption line while the AC voltage was optional. Additionally, blue tooth interface was used to remotely control the solar system. A comparative analysis between various hybrid solutions of DGS/PV/battery, DGS/PV, wind/PV/battery, battery/wind, DGS/battery/wind, and DGS/PV/wind/battery was conducted using HOMER software in the work of [12] and [13]. They proposed PV/DG/battery HES as the most preferable with minimum Net Present Cost (NPC) based on three evaluation criteria which include NPC, LCOE, and rate of CO2 emissions. While PV/wind/DG/battery shows the highest value. The research did not include further renewable energy sources like hydro and biomass.

The authors in [14] discovered that a hybrid system configuration of hydro/PV/DGS/battery was the most suitable to power an off grid community in southern part of Nigeria after a comparative analysis between solar PV, wind, hydro, and diesel generator using HOMER simulation tool based on cost, technology sensitivity and system optimization, using a determinant factors, for example cost of energy (COE), operation and maintenance cost, NPC, excess electricity, capacity shortage, generator fuel consumption rates, load fulfillment, and greenhouse gasses emissions savings. Homer Pro software was used by authors in [15] in carrying out a study in central China on comparative analysis between off grid and grid connected systems. They revealed that grid connected under single rate policy is less economical than that under time-of-use rate policy. The cost of land for installing Solar PV and Wind Turbine has not been considered.

The authors in [2] conducted a data analysis using descriptive and inferential (X2 -Chi square) statistics for the effect of present grid system on rural electrification and rural economy in Nigeria. The researchers used Imo State as a case study by conducting a questionnaire to generate data, from 894 respondents. Their result revealed that the electricity situation in rural areas is appalling and consequently affect the economic activities due to lack of income opportunities. They also emphasized on mini-grids which can served as decentralized system and a priority on localized generation is recommended. The control algorithm was used in [16] to synchronize diesel generator, wind, and solar PV array of a standalone microgrid to a point of common coupling (PCC). A variable step perturbs method was used to achieve MPPT of a solar PV array and maximum wind speed. A simulation was carried out with 2kW prototype. A mathematical method was used in [9] to determine a power consumption of households for an off-grid community in Jos Nigeria and subsequently developed a solar PV system. The results demonstrated that 10 by 275Wp PV modules and 5 by 100Ah batteries can cover an annual energy consumption of approximately 3132kWh. The results also illustrate a technical and economic viability of PV system in electrification of an off-grid community. In addition, stakeholders in the renewable sector can be encourage with this model to offer additional investments in hybrid PV systems in the Country.

A simulation of load profiles of six industries within and near Lagos, Nigeria was demonstrated in [7] and revealed a potential of using off-grid hybrid systems. The result revealed that the use of solar PV hybrid systems (PV/DGS) would boost economic activities in Nigeria by reduction in LCOE, maintenance and running cost, as well as reduction in greenhouse gasses emissions by industries, real estate, education, banking, automobile, and hospitals. An analysis of environmental challenges and development of novel design to solve the environmental problems was carried out by authors in [17]. The rate of greenhouse gasses (GHG) emissions by different hybrid system configurations were compared. The results revealed that emission of carbon footprint from PV systems was found to be lower than emissions reported from the burning of oil and a reduction of 42% in GHG emissions can be achieved by recycling solar cell materials.

The authors in [14] suggested a solar PV system for Sindh community in Pakistan after computing the tilt angle and conducted economic feasibility studies. Their result revealed that, solar PV system offers electrical energy at low cost than conventional sources. Moreover, if all the chosen off-grid isolated rural regions can embrace the solar PV system, it could alleviate maximum CO_2 yearly emissions. Therefore, the research shall support the government in development of off-grid solar PV power generation system in the isolated rural areas of Pakistan. The authors in [18] modelled, analyzed, and compared a combination of eleven hybrid renewable energy systems for off-grid community using HOMER Pro software to detect the best performing and optimum plan configuration. The first scenario consists of a PV/Wind/DG, while the second scenario is a combination of PV/Wind/DG/Battery. To find the best sizing of different off-grid power plant, the base-case of diesel generator was considered to meet the electrical load demand. Based on the optimization outcomes the proposed PV/wind/DG/battery/converter system outpaced other options with regards to the NPC, renewable fraction, cost of energy, and CO_2 emission, respectively.

A recommendation was made on how to reform Nigerian power sector in research carried out by [19] through the application of laws and policies which will affect the economic, social and national growth. They analyzed the reforms advocated by laws and policies and the level to which they improve or otherwise the power sector in the country. A review and analysis of 90 relevant articles on rural electrification from renewable energy sources was conducted by [20] to mitigate the challenges of generation, transmission, and distribution in Nigeria. The outcome of the research introduced an integrated framework that can be served as road map to improve energy access in Nigeria. The authors in [21] conducted study using Homer Pro and developed a hybrid model of PV/DC generator for both AC and DC loads. A comparative analysis of multiple options has been carried out based on fuel consumption, emission of greenhouse gasses and cost to select the most optimized system configuration.

The authors in [8] revealed that about 60% (74 million) Nigerians do not have access to electricity while another 94% (171 million) do not have access to clean energy. They also discovered that ridiculous installation and maintenance cost, limited private sector investment affects the harnessing of available renewable resources in Nigeria. The researchers in [22] collected and analyzed wide range of data using Homer Pro for system design and Simulink/MATLAB for dynamic modelling of various renewable energy resources to provide DC power solution for off grid communities. Researchers in [23] performed a comparative analysis between different system configurations of PV/DG, PV/DG/Battery, and DG/Battery. They used Homer Pro in conducting simulation and comparison based on cost, sensitivity, and system optimization to select the best system configuration.

2. METHODOLOGY

In this section, the methodology used in this study to achieve the feasibility of single and hybrid renewable energy sources applicable to off-grid communities was provided. A remote community in northern Nigeria is selected, based on solar irradiation, economic activities, distance from existing grid and population density. The MATLAB/Simulink model was used to size system components and Homer Pro software for system design, simulation and comparative analysis of different system configurations to select the most suitable for a community.

2.1 Site Selection

Falde village in northern Nigeria is chosen as the case study. Falde (12.597614°N, 3.80395°E) is an off-grid community located in Arewa local government area of Kebbi State, Nigeria with an estimated population of about 750 people (i.e 150 households with an estimated 5 people per household). Based on the interview conducted, most of its population are farmers whose daily schedule is to use morning hours for their farming activities and evening for home activities. The pattern of their energy consumption is directly proportional to their daily schedule. The community uses firewood for cooking and kerosene lamp for lighting, while some households charge their rechargeable lanterns and phones in households that can afford small captive generators which can only be used for a few hours daily (usually at night) due to financial burden imposed on them. The actual location from google earth is shown in Figure 1.

Figure 1: Falde village map (Google Earth)

Table 1: Map Data Site Information for Falde Community [24]

Description	*Quantity*
Specific Photovoltaic Power Output (PVOUT)	4.624 kWh/kWp/day
Direct Normal Irradiance (DNI)	4.148 kWh/m^2/day
Global Horizontal Irradiance (GHI)	5.848 kWh/m^2/day
Diffuse Horizontal Irradiance (DHI)	2.815 kWh/m^2/day
Global Tilted Irradiation at Optimum Angle (GTI opta)	6.600 kWh/m^2/day
Optimum Tilt of PV Module (OPTA)	17/180 ◦
Air Temperature (TEMP)	25.2 °C
Terrain Elevation (ELE)	237 m
Coordinate	12.597614°N, 003.80395°E

Table 1 gives the specific solar energy resource values for the research area. The global tilted irradiation for the site is 6.6 kWh/m^2/day at 17/180◦ which shows a good potential for solar power plant. The global position of the site as well as its terrain elevation were 12.597614°N, 003.80395°E and 237 m respectively.

2.1.1 Data Processing

The system is modelled using MATLAB codes/Simulink (MATLAB Function) and population density is used as varying factor to calculate the power and energy demand of individual user group and community at large. When population density increased by five (5), automatically the number of households increased by one (1) and when the population doubled, other parameters too doubled in size. The generalized Simulink/MATLAB model is shown in figure 2.

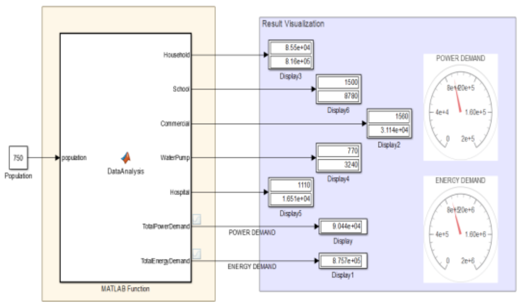

Figure 2: Generalized SIMULINK/MATLAB model

The data obtained was analyzed to determine the type of system suitable for a particular community. The estimated number of households in Falde community is one hundred and fifty (150) with an estimated number of five (5) persons per household. Therefore, estimated population density of the community is seven hundred and fifty (750) people.

Table 2: Estimated load demand for 150 households

Load Type	*Qty*	*Power (W)*	*Total Power (W)*	*Time (hrs)*	*Energy (Wh/day)*
LED Lights	5	10	50	8	400
Ceiling Fans	2	70	140	18	2520
TV	1	50	50	4	200
Others	1	100	100	14	1400
Average Daily Load per Household			340.00		4520.00
Average Daily Load for 150 Households			51,000.00		678,000.00

The estimated energy demand for 150 households and for the entire community are tabulated in Tables 2 and 3 respectively based on load type, their power ratings, number of hours in operation in a day and average energy demand in Watt-hour per day.

The daily power and energy demand obtained from generalized model were used in sizing system components using mathematical method. An hourly load data profile for a single day serves as an input for simulation with HOMER Pro. A daily load profile for the month of January and annual profile were developed by Homer Pro software using 24-hour energy consumption of Falde community as shown in Figure 3. The average energy demand is 726.650kWh/day while the peak load is 90.86kW.

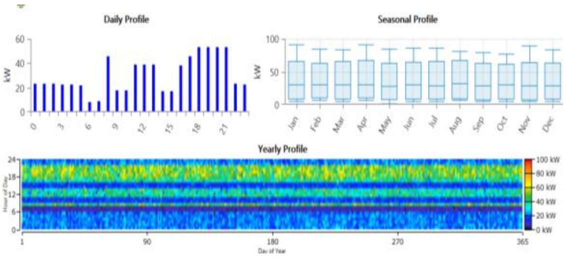

Figure 3: Falde daily energy demand profile [25]

Figure 3 described the daily, yearly and seasonal variations in the energy demand of the study area obtained from NASA through the Homer Pro software. The peak load was 90.86 kW and average energy demand per day stood at 726.650 kWh. The seasonal variations fairly follow the same pattern with peak load not exceeding 100 kW.

2.2.1 Hybrid Renewable Energy System Components and Configuration

The system components used in this study are diesel generating set, Solar PV array, Charge controller, Inverter and Battery bank. Details of the system components are given as follow.

2.2.2 Diesel Generating Set (DGS)

Diesel generator is one of the major alternatives in electrifying off-grid communities as a single source to replace multiple petrol generators. Even though, the cost of running a generator is above three-times that of the national grid, it is widely used due to its low capital cost. However, it releases many hazardous air contaminants and greenhouse gasses which are highly toxic to the environment. Due to technical and monitoring problems it is difficult to obtain all required data for greenhouse gasses emissions. The best way is to use the amount of fuel consumption to estimate the CO_2, CO, NO_2 and SO_2 emissions [26].

The capacity of centralized diesel generator can be determined using a peak power demand of a selected community as illustrated in equation (1) below [27].

$$DGS = Pp(1 + \%losses) \div PF \qquad (1)$$

where, DGS is the Diesel Generating Set Size,
Pp is the Peak Power Demand
PF is the Power Factor

The consumption of one liter of fuel emits a CO_2 within a range of 2.4-2.8kg/ltr. However, in off-grid rural communities, diesel generators can be replaced with solar PV system due to its ability to reduce greenhouse gasses emissions. An estimation indicates that by 2050, 11% of global electricity generation will be provided from PV systems which resulted in the prevention of 2.3gigatones of CO_2 emissions per year [26]. The diesel generator consumption rate (F) is presented in equation (2).

$$F=0.246P_{out} + 0.08415P_r \qquad (2)$$

where, F is fuel consumption rate (liters/hour}
P_{out} is the actual operating output power (kW) and
P_r is rated power of diesel generator

Table 4 shows an average fuel consumption for different generator sizes and loads. It also described the fuel consumptions in relation to capacity and loads of a Generating Set. Based on the Table 2, a higher capacity generator may consume less fuel than a lower capacity generator when the latter services more load than the former.

2.2.3 Photovoltaic Array

This is an assembly of multiple modules that are interconnected. Higher voltage can be achieved with series connection while higher current can be obtained with parallel connection. A suitable connection method can be achieved to have an optimized power output [28]

To size a PV array, a solar irradiance, peak sun hour and standard test conditions irradiance can be determined for a selected community to calculate a total power for the array. Therefore, total power output of the array can be determined by dividing an average energy demand by peak sun hour as given in equation (3) [29]. Solar irradiance of Falde community was sourced from NASA through HOMER Pro and used in sizing the PV array as shown in Figure 4.

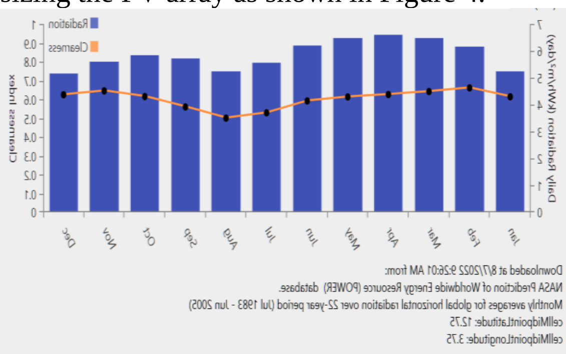

Figure 4: Solar irradiance of Falde Community [25]

Figure 3 provides the monthly variations of solar irradiation of the Falde community. The month of April recorded the highest solar irradiation while the least value was in August. The data also revealed that the study area has a fairly stable solar irradiation. The total power required per day based on the available resource was obtained from equation (3).

$$TPR = \frac{AEd + \%losses}{psh} \qquad (3)$$

Where, TPR is the Total Power Required per day
AEd is the Average Energy Demand per day
psh is the Peak Sun Hour

2.2.4 Converters

This device converts the output of solar modules to supply AC loads. The size of an inverter can be the same as the peak power demand of appliances with the same nominal voltage as that of battery. There is need for 20% tolerance in case of motor or compressor loads to handle starting surge current [30]. Then an inverter can be selected based on available capacity from manufacturers, such as 3 kVA, 5kVA, 10 kVA, 20 kVA, 30kVA and 60kVA etc.

2.2.5 Battery Bank

A battery bank is a combination of batteries used in storing energy for use when sun is not shining. The most common batteries used in solar PV systems are lead-acid and lithium-ion batteries. At night and cloudy days, the battery bank can sustain the required energy needed by electrical load [30]. In this study, lead acid battery with 60% depth of discharge, 200Ah, 12V is considered. The capacity of battery bank can be calculated by using equation (4).

$$BC = \frac{AEd \times DoA}{Vs \times DoD \times Eb} \qquad (4)$$

where, BC is the Battery Bank Capacity (Ah);
AEd is the Average Energy Demand per day
DoA is the Days of Autonomy
DoD is the Depth of Discharge
Vs is the System Voltage
Eb is the Battery Efficiency

2.3 System Configuration

The study varies the configuration of system components to get different results. The study made a comparison between six (6) system configurations as listed below:

1. Centralized generating set
2. Centralized PV system.
3. PV system with battery storage and load.

4. PV system with diesel generating set and load.
5. Diesel generating set, battery storage and load.
6. Diesel generating set, PV system, battery storage and load.

Based on the designed parameters, various configurations of systems have been modelled using Homer Pro software. The Schematic diagram of hybrid system configuration of PV/DGS/Battery storage is shown in figure 5.

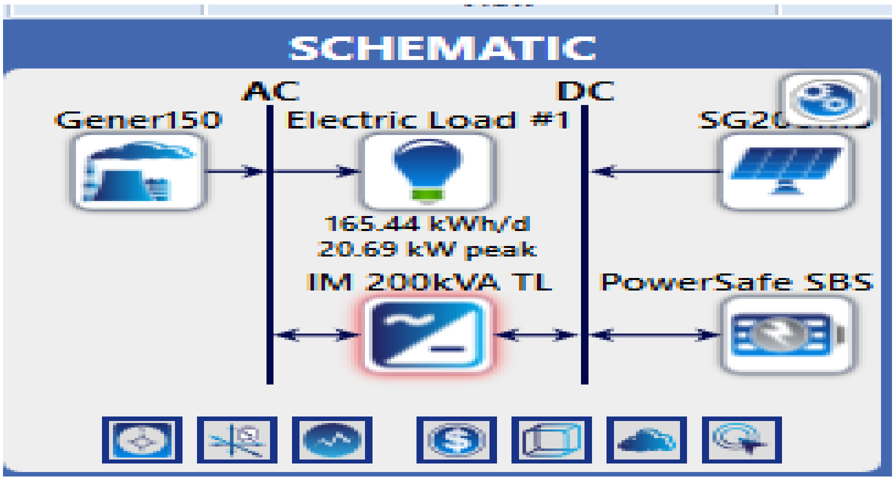

Figure 5: Schematic diagram of hybrid solar PV system using Homer Pro

To investigate the cost of developing a single source (e.g centralized generating set or solar PV system) and hybrid solar systems (Solar PV/DGS/batteries, solar PV/DGS, DGS/battery) alongside the running and maintenance cost, Homer Pro software was used. The estimated cost for the system components is tabulated in table 3.

Table 3: Estimated Energy demand for Falde Community

Consumer Type	*Consumer No.*	*Total Power (W)*	*Total Energy Demand (Wh)*	*kWh*
Households	150	51,000.00	678,000.00	678.00
School	2 offices, 6 classes	8,090.00	8,090.00	8.09
Hospital	5 rooms	780.00	11,790.00	16.51
Water pump &Street light	1&1	530.00	4,110.00	4.11
Commercials	10 shops	1,290.00	24,660.00	24.66
Average Daily Load		61,690.00	726,650.00	726.65
Average Yearly Load		22,516.85kW/year	265,227.25kWh/year	265.23MWh/year

HOMER Pro software was used in carrying out a comparative analysis of various system configurations based on cost, emission of greenhouse gasses, sensitivity analysis, and optimization to select the best system suitable for a community.

3.0 Results and Discussion

The generalized system model is designed using Simulink/MATLAB function and used in calculating the power demand, energy demand and load profile to determine the system size for different configurations of selected off-grid community. The power demand, energy demand and load profile are used in determining the system size for different configurations of selected off-grid community. The estimated peak power and energy demand of the community were 90.86kW/day and 726.65kWh respectively. The system components consist of 2x100kVA generating set, 426 solar PV modules, 5x30kVA inverters, 33x100A charge controllers and 149 of 200AH, 12V battery bank. HOMER Pro was used for comparative analysis of six (6) different system configurations of centralized generating set, centralized PV generation system, DGS/PV, DGS/battery, and DGS/PV/battery. A sensitivity evaluation was performed to determine system performance, while varying input variables that directly affect the operational behaviour of the system configurations. The maximum capacity shortage of 3% was set for 25 years of project lifespan and a diesel fuel price of ₦700/L.

The energy demand of Falde community with an estimated population density of 750 and an approximate number of households of 150 is calculated as 726.65kWh/day and 265.23MWh/year of energy demand, an average power demand of 61.69kW and peak power of 90.86kW. Figure 6 shows the estimated load profile for the entire community.

Table 4: Diesel Generator Fuel Consumption

GENERATOR SIZE	APPROXIMATE DIESEL FUEL CONSUMPTION			
	1/4 Load (litres/hr)	**1/2 Load (litres/hr)**	**3/4 Load (litres/hr)**	**Full Load (litres/hr)**
8KW/10KVA	0.9	1.2	1.7	2.1
10KW/12KVA	1.0	1.4	2.1	2.6
12KW/15KVA	1.3	1.8	2.6	3.2
16KW/20KVA	1.7	2.4	3.5	4.3
20KW/25KVA	2.1	3.0	4.3	5.4
24KW/30KVA	2.6	3.6	5.2	6.4
32KW/40KVA	3.4	4.8	7.0	8.6
40KW/50KVA	4.3	6.0	8.6	10.7
60KW/75KVA	6.4	9.0	12.7	16.1
80KW/100KVA	8.3	11.9	16.1	21.4
120KW/150KVA	10.9	17.3	24.1	32.1
160KW/200KVA	14.1	22.9	32.7	42.8
200KW/250KVA	17.4	28.6	40.8	53.5
280KW/350KVA	23.7	39.3	56.0	74.9
400KW/500KVA	33.3	55.6	79.6	107.0

Table 5: Cost for the components

S/N	*Description*	*Quantity*	*Unit cost (₦)*	*Total (₦)*
1	380Wp, 48V Solar PV Module	426	117,000.00	49,842,000.00
2	200Ah, 12V Battery	149	162,500.00	24,212,500.00
3	30kVA Inverter	5	1,350,000.00	7,250,000.00
4	100A, 24V Charge Controller	33	13,999.00	321,977.00
6	200kVA Diesel generator	1	9,450,000.00	9,450,000.00
7	Cable and Accessories	Lot	1,000,000.00	1,000,000.00
8	Miscellaneous	Lot	500,000.00	500,000.00
	Total Cost			**92,576,477.00**

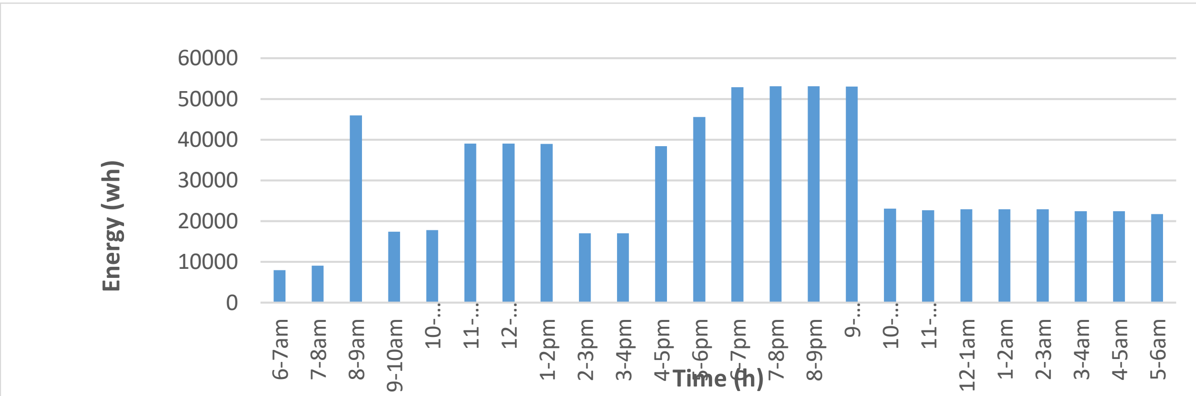

Figure 6: Load Profile for Falde Community

3.1 Comparative Analysis

Tables 6 and 7 below present the results of the comparative analysis between the six hybrid energy options obtained from Homer pro simulations.

The DGS/PV/Battery system configuration has the highest NPC and operating cost while single source solar PV system has the lowest NPC and operating cost. The comparison of different system configurations based on cost and energy production using Homer Pro is shown in table 6. The estimated energy demand of Falde Community per year is 265.23MWh/year. Table 6 shows a comparative analysis based on cost, energy production and fuel consumption per year for different system configurations.

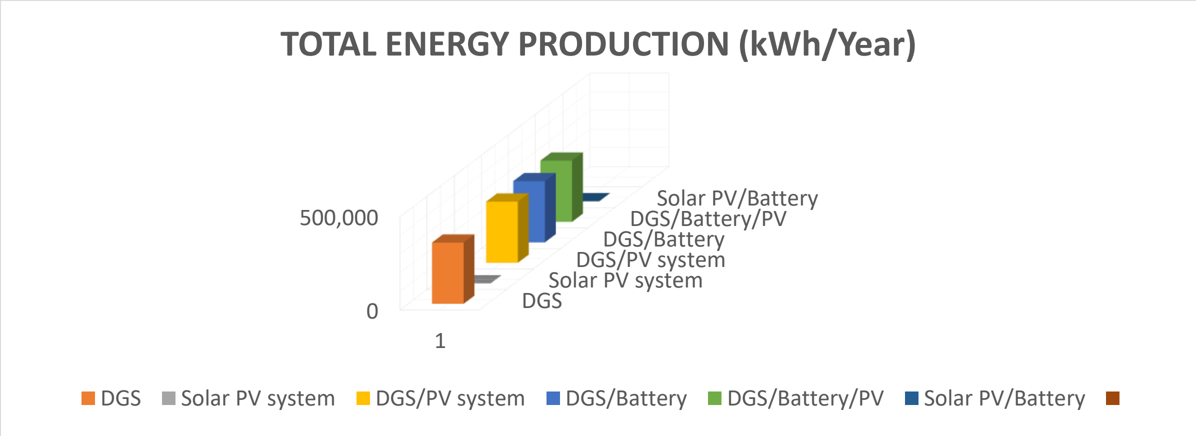

Figure 7: Total Energy Production per Year for all the Six Configurations

From Figure 7, DGS and DGS/Battery configurations produced the same energy per year and the highest of all the configurations followed closely by Solar PV/Battery and DGS/Battery/PV configurations. The least energy production was from solar PV system. It can also be deducted from Figure 7 that out of the six configurations, the *Solar PV* and *Solar PV/Battery* configurations are the only options that cannot support the yearly energy demand of the research location.

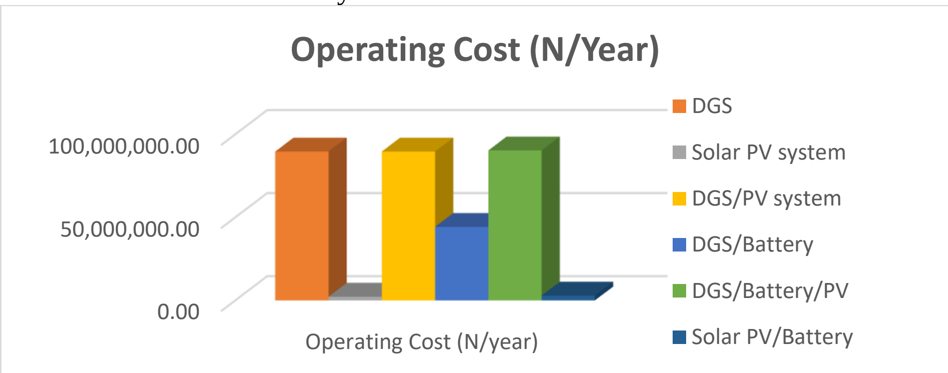

Figure 8: Cost of Operation for all the Six Configurations.

Figure 8 described the various costs of operation of the different configurations, *The Solar PV* configuration has the least operating cost per year of all the other configurations followed by the *solar PV/Battery* Configuration. The Figure also illustrated the fact that *DGS/Battery/PV* configuration is the expensive option to operate owing to its highest cost of operation.

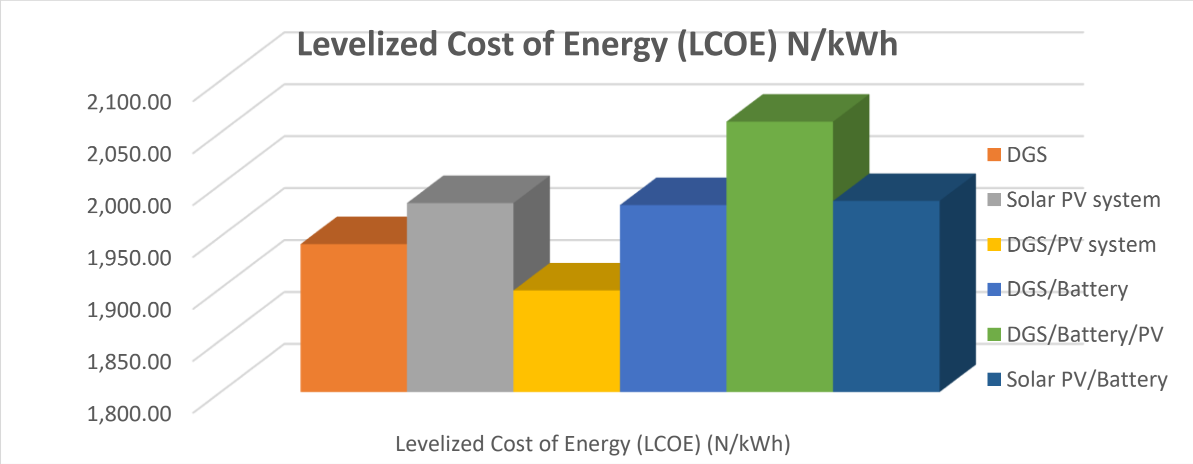

Figure 9: Levelized Cost of Energy (LCOE) per unit for all the Configurations

Table 6: Comparative Study between Different Configurations

Configuration	*Total Energy Production (kWh/year)*	*Net Present Cost (₦)*	*Levelized Cost of Energy (LCOE) (₦/kWh)*	*Operating Cost (₦/year)*	*Fuel Consumption (L/year)*
DGS	328,500	1,735,193,000.00	1,942.45	89,618,540.00	114,406
Solar PV system	104	433,823,300.00	1,982.00	2,214,684.00	0
DGS/PV system	328,500	1,880,064,000.00	1,897.87	89,607,130.00	114,406
DGS/Battery	328,462	1,769,089,000.00	1,980.00	44,234,400.00	114,393
DGS/Battery/PV	328,462	2,041,923,000.00	2,060.39	90,281,350.00	114,393
Solar PV/Battery	415	467,207,100.00	1,984.00	2,883,468.00	0

Table 7: Environmental Analysis

Pollutant Emissions (kg/year)	**DGS**	*PV System*	*DGS / PV*	*DGS / Battery*	*DGS / Battery / PV*	*PV / Battery*
Carbon dioxide	300,200	0	300,165	299,412	220,900	0
Carbon monoxide	1,423	0	1,423	1,419	1,047	0
Unburned Hydrocarbons	82.4	0	82.4	82.2	60.6	0
Particulate Matters	6.41	0	6.41	6.39	4.71	0
Sulphur Dioxide	733	0	733	731	540	0
Nitrogen Dioxide	1,627	0	1,627	1,623	1.197	0

The Cost per unit of energy is presented in Figure 9. The *DGS/PV* configuration has the least cost per unit of all the configurations followed by the centralized *DGS* configuration. The option with the highest cost per unit of energy is the *DGS/Battery/PV* configuration in addition to being the option with the highest yearly cost of operation.

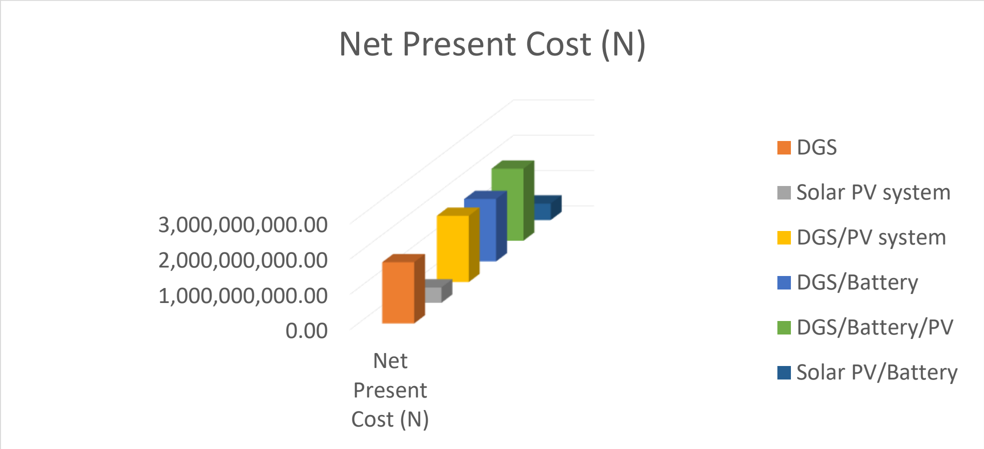

Figure 10: Cost of Production for all the Six Configurations

The current expense for each of the configuration is presented in Figure 10. It can be seen that the *Solar PV* configuration has the least net present cost while the *DGS/Battery/PV* has the highest net present cost. It can also be deducted from the figure that Solar PV/Battery option has a relatively lower net present cost compared to other configurations.

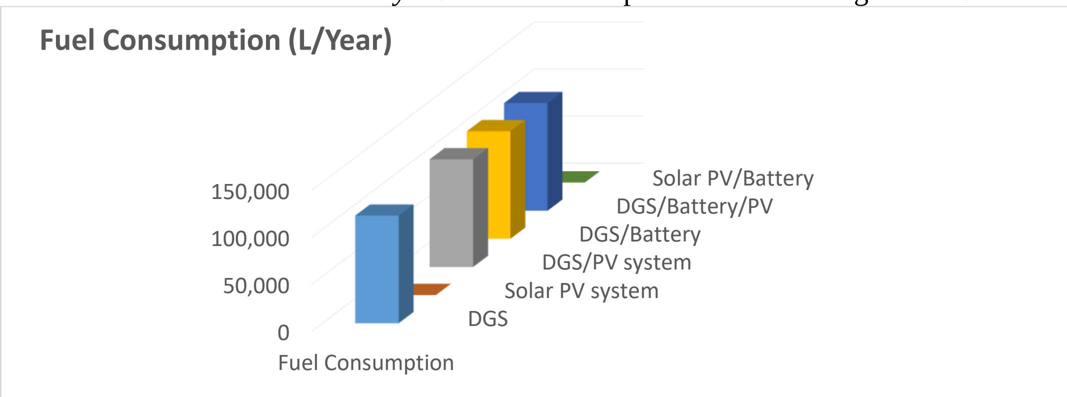

Figure 11: Fuel Consumption in Number of Litres per Year for all the Configurations

Figure 11 compared the fuel consumptions of the configurations that utilizes fuel. It can be seen that the consumption of fuel from the configurations is fairly the same with insignificant differences. However, the centralized solar PV and Solar PV/Battery does not require fuel for their operations.

Table 7 shows the amount of CO_2, CO NO_2 and SO_2 emissions according to different configurations. The emission of greenhouse gases (GHGs) in single and hybrid sources are ascribed to the fuel consumption level of DGS. In this research work, the CO_2 and other GHGs emissions were used to determine the environmental effects of different configurations.

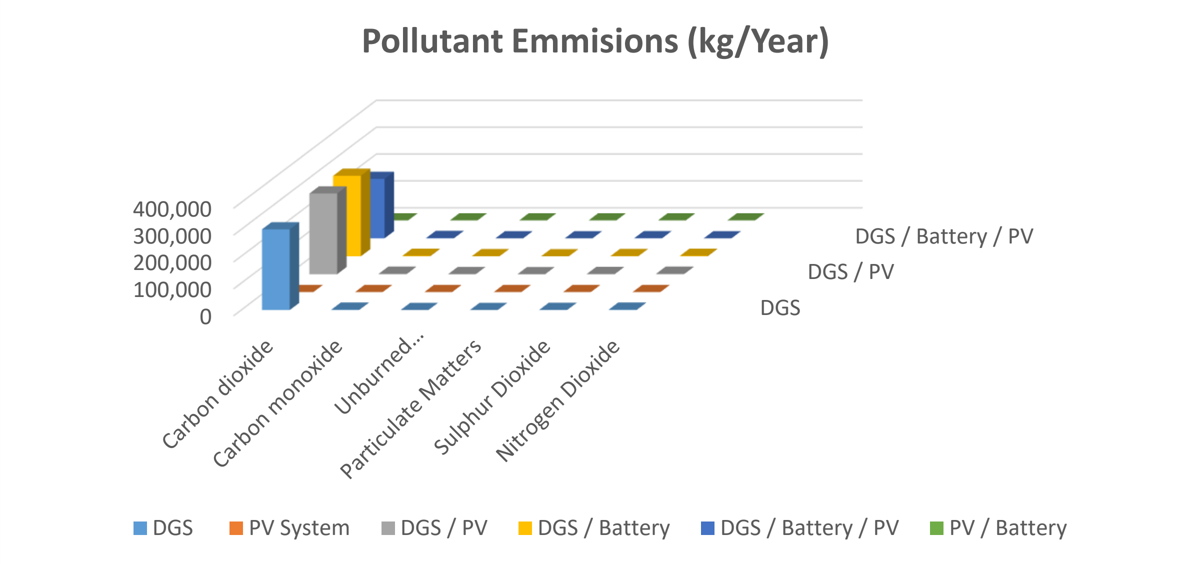

Figure 12: Pollutant Emissions of Greenhouse gases in the hybrid configurations

CO_2 is the dominant greenhouse gas emissions in all the four hybrid configurations that utilizes DGS followed by NO_2 and CO emissions. The other pollutants are relatively lower than the above-mentioned gases.

4.0 Conclusion

As the number of rural off-grid communities keep increasing in Nigeria, so as the need to provide reliable power for daily need. A comparative analysis was carried out using Homer Pro on six (6) different system configurations based on cost, emission of greenhouse gasses, sensitivity, and system optimization to select the most suitable system configuration for a community. Based on the results obtained, the most suitable system configuration according to the research for Falde Community in terms of least value of NPC (₦433,823,300.00) is Solar PV system, in terms of energy productions are DGS (328,500kWh/year) and DGS/PV system (328,500kWh/year), while in terms of greenhouse gasses emissions are Solar PV system (Zero emissions) and PV/Battery (Zero emissions), but in terms of reliability is DGS/PV/Battery configuration. The cost of land has not been considered, but the large land area required for installing PV is a practical problem for application. Future study can be conducted by taking the land costs of each region into account based on local policies.

REFERENCES

L. Olatomiwa, R. Blanchard, S. Mekhilef, and D. Akinyele, “Hybrid renewable energy supply for rural healthcare facilities: An approach to quality healthcare delivery,” *Sustainable Energy Technologies and Assessments*, vol. 30, pp. 121–138, Dec. 2018, doi: 10.1016/j.seta.2018.09.007.

C. Uzoma *et al.*, “Centralized Electricity Grid and the Rural Economy of Nigeria,” in *IOP Conference Series: Earth and Environmental Science*, May 2021, vol. 730, no. 1. doi: 10.1088/1755-1315/730/1/012015.

C. Ogbonnaya, C. Abeykoon, U. M. Damo, and A. Turan, “The current and emerging renewable energy technologies for power generation in Nigeria: A review,” *Thermal Science and Engineering Progress*, vol. 13. Elsevier Ltd, Oct. 01, 2019. doi: 10.1016/j.tsep.2019.100390.

National Control Center, “Nigeria Electricity System operator report,” *https://www.nsong.org/*, May 20, 2022.

Nigerian Economic Sustainability Plan, “Solar Power Naija,” *https://nep.rea.gov.ng/federal-governments-5milion-solar-connections-program/* , 2021.

A. Demirbas, M. Kabli, R. H. Alamoudi, W. Ahmad, and A. Basahel, “Renewable energy resource facilities in the Kingdom of Saudi Arabia: Prospects, social and political challenges,” *Energy Sources, Part B: Economics, Planning and Policy*, vol. 12, no. 1. Taylor and Francis Inc., pp. 8–16, Jan. 02, 2017. doi: 10.1080/15567249.2014.996303.

A. A. Adesanya and J. M. Pearce, "Economic viability of captive off-grid solar photovoltaic and diesel hybrid energy systems for the Nigerian private sector," *Renewable and Sustainable Energy Reviews*, vol. 114, Oct. 2019, doi: 10.1016/j.rser.2019.109348.

A. A. Popoola and B. M. Adeleye, "Access and Limitations to Clean Energy Use in Nigeria," in *Lecture Notes in Energy*, vol. 77, Springer, 2020, pp. 241–262. doi: 10.1007/978-3-030-43578-3_12.

O. C. Akinsipe, D. Moya, and P. Kaparaju, "Design and economic analysis of off-grid solar PV system in Jos-Nigeria," *J Clean Prod*, vol. 287, Mar. 2021, doi: 10.1016/j.jclepro.2020.125055.

Y. Sawle, S. C. Gupta, and A. K. Bohre, "Review of hybrid renewable energy systems with comparative analysis of off-grid hybrid system," *Renewable and Sustainable Energy Reviews*, vol. 81. Elsevier Ltd, pp. 2217–2235, Jan. 01, 2018. doi: 10.1016/j.rser.2017.06.033.

Ga. IEEE International Conference on Direct Current Microgrids 1. 2015 Atlanta, Institute of Electrical and Electronics Engineers, IEEE Power Electronics Society, Ga. IEEE International Conference on DC Microgrids 1 2015.06.07-10 Atlanta, Ga. IEEE International Conference on Direct Current Microgrids 1 2015.06.07-10 Atlanta, and Ga. ICDCM 1 2015.06.07-10 Atlanta, *2015 IEEE First International Conference on DC Microgrids (ICDCM) 7-10 June 2015*. IEEE, 2015.

A. I. Hassane, D. H. Didane, A. M. Tahir, R. M. Mouangue, J. G. Tamba, and J. M. Hauglustaine, "Comparative analysis of hybrid renewable energy systems for off-grid applications in chad," *International Journal of Renewable Energy Development*, vol. 11, no. 1, pp. 49–62, Feb. 2022, doi: 10.14710/ijred.2022.39012.

J. O. Oladigbolu, Y. A. Al-Turki, and L. Olatomiwa, "Comparative study and sensitivity analysis of a standalone hybrid energy system for electrification of rural healthcare facility in Nigeria," *Alexandria Engineering Journal*, vol. 60, no. 6, pp. 5547–5565, Dec. 2021, doi: 10.1016/j.aej.2021.04.042.

L. Xu, Y. Wang, Y. A. Solangi, H. Zameer, and S. A. A. Shah, "Off-grid solar PV power generation system in Sindh, Pakistan: A techno-economic feasibility analysis," *Processes*, vol. 7, no. 5, May 2019, doi: 10.3390/pr7050308.

M. M. Wei, J. Z. Wang, and Z. J. Huang, "Comparative analysis of hybrid systems for on-grid and off-grid applications in central China: Case study of university dormitory in Ma'anshan," in *IOP Conference Series: Earth and Environmental Science*, Mar. 2019, vol. 238, no. 1. doi: 10.1088/1755-1315/238/1/012028.

M. Rezkallah *et al.*, "Comprehensive Controller Implementation for Wind-PV-Diesel Based Standalone Microgrid," in *IEEE Transactions on Industry Applications*, Sep. 2019, vol. 55, no. 5, pp. 5416–5428. doi: 10.1109/TIA.2019.2928254.

M. Tawalbeh, A. Al-Othman, F. Kafiah, E. Abdelsalam, F. Almomani, and M. Alkasrawi, "Environmental impacts of solar photovoltaic systems: A critical review of recent progress and future outlook," *Science of the Total Environment*, vol. 759, Mar. 2021, doi: 10.1016/j.scitotenv.2020.143528.

K. Elmaadawy *et al.*, "Optimal sizing and techno-enviro-economic feasibility assessment of large-scale reverse osmosis desalination powered with hybrid renewable energy sources," *Energy Convers Manag*, vol. 224, Nov. 2020, doi: 10.1016/j.enconman.2020.113377.

V. K. Abanihi, S. O. Ikheloa, and F. Okodede, "Overview of the Nigerian Power Sector," *American Journal of Engineering Research (AJER*, no. 7, pp. 253–263, 2018, [Online]. Available: www.ajer.org

B. Ugwoke, O. Gershon, C. Becchio, S. P. Corgnati, and P. Leone, "A review of Nigerian energy access studies: The story told so far," *Renewable and Sustainable Energy Reviews*, vol. 120. Elsevier Ltd, Mar. 01, 2020. doi: 10.1016/j.rser.2019.109646.

A. O. Rousis, D. Tzelepis, I. Konstantelos, C. Booth, and G. Strbac, "Design of a hybrid ac/dc microgrid using homer pro: Case study on an islanded residential application," *Inventions*, vol. 3, no. 3, Sep. 2018, doi: 10.3390/inventions3030055.

J. Kitson *et al.*, "Modelling of an expandable, reconfigurable, renewable DC microgrid for off-grid communities," *Energy*, vol. 160, pp. 142–153, Oct. 2018, doi: 10.1016/j.energy.2018.06.219.

M. Madziga, A. Rahil, and R. Mansoor, "Comparison between three off-grid hybrid systems (Solar photovoltaic, diesel generator and battery storage system) for electrification for gwakwani village, South Africa," *Environments - MDPI*, vol. 5, no. 5, pp. 1–21, May 2018, doi: 10.3390/environments5050057.

Global Solar Atlas, "Falde Community Map Data Site Information," *https://globalsolaratlas.info/map?c=12.597614,3.80395,11&s=12.597614,3.80395&m=site*, 2022.

Homer Pro, "Hybrid Optimization of Multiple Energy Resources," *www.homerenergy.com*, 2022.

IEEE Staff and IEEE Staff, *2012 International Conference on Green and Ubiquitous Technology.*

K. Y. Kebede, "Viability study of grid-connected solar PV system in Ethiopia," *Sustainable Energy Technologies and Assessments*, vol. 10, pp. 63–70, Jun. 2015, doi: 10.1016/j.seta.2015.02.003.

B. Kiris, O. Bingol, R. Senol, and A. Altintas, "Solar array system layout optimization for reducing partial shading effect," in *Acta Physica Polonica A*, Jul. 2016, vol. 130, no. 1, pp. 55–59. doi: 10.12693/APhysPolA.130.55.

M. Chandel, G. D. Agrawal, S. Mathur, and A. Mathur, "Techno-economic analysis of solar photovoltaic power plant for garment zone of Jaipur city," *Case Studies in Thermal Engineering*, vol. 2, pp. 1–7, 2014, doi: 10.1016/j.csite.2013.10.002.

Leonics Support, "How to Design Solar PV System," *https://www.leonics.com/support/article2_12j/articles2_12j_en.php*, 2015.