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Feasibility Study of Hybrid Renewable Power System for Off-Grid Rural Electrification in Niger State, Nigeria

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Abstract- Persistent fossil fuel combustion has a significant environmental impact. As a result, shifting to a renewable energy system or hybridization of alternative energy systems can help to minimize the harmful gases emitted by fossil fuels. The feasibility assessment of a hybrid PV/diesel and battery system setup in F.M Maitumbi village in Niger State, Nigeria is presented in this paper. The feasibility analysis was conducted using HOMER optimization software. The optimum hybrid PV/diesel system configuration shows how a significant amount of CO_2 can be reduced, as well as the impact of PV penetration. Comparison of the system configurations of PV-diesel-battery, PV-diesel without battery, Standalone diesel and standalone PV system based with \$0.4901/kW, \$0.642/kW, \$0.640/kW and \$0.699/kW respectively as their cost of energy. A PV-diesel-battery Hybrid Power System (HPS) was designed for the geographical region under consideration, taking into account net present costs, energy expenses, CO_2 emissions, excess electricity generated, and renewable penetration.

Indexed Terms- Renewable energy, Cost of Energy, Emission, HOMER, Irradiance and Niger State

I. INTRODUCTION

Rural electrification is an effective method for the long-term development of such communities in both developed and developing countries. There was a significant interest in the development of wind/PV, PV/diesel, wind/diesel, and wind/PV/diesel hybrid power systems (HPSs) ranging from medium to large scale for the electrification of various rural areas across the world [1]. According to a survey done by the United Nations Environment Program (UNEP), an estimated 1.7-2.0 billion people worldwide lack grid access, with the bulk of these people living in impoverished rural areas [2], [3]. The inequitable distribution of electrical energy is caused by a variety of reasons, including; the remoteness of rural communities from the grid, which makes it uneconomical to extend the grid to such sparsely populated areas, and the steep topography of the location [4]. And this is the main objective behind the ongoing research on Hybrid Power Systems (HPSs) and Renewable Energy Resources (RESs). Depletion of fossil fuels and rising energy consumption as a result of rapid worldwide population expansion are also key causes. Solar energy generation via photovoltaic (PV) arrays has the advantage of being emission-free and using renewable resources. Even though the most advanced solar panels can convert roughly 22% of the sun's spectrum radiation into electricity, a significant amount of money and research effort is being invested in making solar module technology as efficient as feasible [5], [6].

The mix of a solar photovoltaic system and a diesel generator has various advantages and helps to avoid supply intermittency. Solar photovoltaic technology has been identified as a technology that is friendly to the environment and requires only energy from the sun. A diesel generator, solar panels, a battery bank for storage, and a DC-AC power converter are all part of the hybrid power system described in this study. Other combinations mentioned in numerous literatures are not restricted to PV/diesel/battery combinations in Hybrid Power Systems (HPSs). The criterion for selecting a hybrid system for a specific location are determined by the geography of the area under consideration, load demand, seasonal energy resource availability, and energy storage cost, among other factors. [7], [8].

II. SOLAR ENERGY BACKGROUND

Nigeria is in west Africa, surrounded on the north by Niger, on the west by Benin, on the east by Cameroon, on the northeast by Chad, and on the south by the

Atlantic Ocean. It is located between 44º 16' and 13º 53' north of the equator, and between 2o 40' and 14o 24' east of the Greenwich meridian. It has a land size of 932,768 square kilometers and a population of approximately 200 million people (National Commission for Mass Literacy). Nigeria is located in a high-sunshine zone with significant solar energy potential. The yearly average of total solar radiation varies from 3.5kWh/m2/day along the coast to roughly 7Kwh/m2/day in semi-arid areas in the far north. The country receives approximately 19.8MJ/m2/day of solar energy on average. Daily sunshine hours range from 4 to 9 hours per day on average, with the number of hours increasing from the south to the north. It is conceivable to generate more than one hundred times the current generation of Nigeria if solar modules are deployed to cover 1% of the country's land area [9].

Niger is one of Nigeria's 36 states, located in the northwestern part of the country. It has a population of around 5 million people and is divided into 25 Local Government Areas. Renewable energy sources such as sun, hydro, wind and biomass have been bestowed upon the state by God. Due to Niger's high solar irradiance, a number of companies are flocking to the country to form partnerships with the state government or investors in order to generate electricity using solar PV.

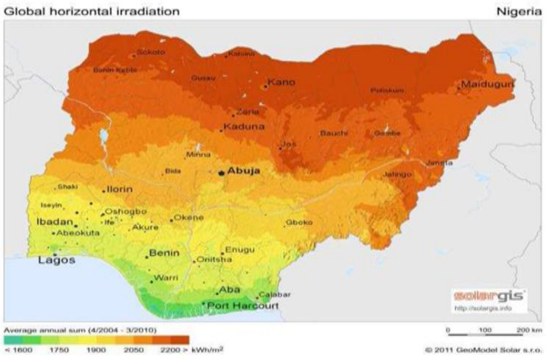

Figure 1: Global horizontal irradiation (GHI) of Nigeria [10]

From Figure 1, it is clear that, Niger state has an average annual total solar radiation not less than 2050kWh/m^2

2.1 Homer Simulation Software

The National Renewable Energy Laboratory (NREL) in the United States developed the HOMER software, which was used in this study. The software was chosen because of its unlimited accessibility for micro grid modeling as well as its ease of use. The HOMER simulation tool makes planning hybrid systems, whether grid-connected or stand-alone, more easier. The HOMER optimization algorithm and sensitivity analysis examine the techno-economic viability of a wide variety of technological solutions while taking into consideration the variance in technology cost, energy resource availability, and electrical load.

A detailed sequential simulation and optimization model is provided by the hybrid optimization model for electric renewables (HOMER) program. It can be used for a wide range of projects, including local and large-scale power systems. HOMER can simulate both the technical and economic aspects of the study, and the optimal arrangement is then subjected to a sensitivity analysis technique in which many optimizations are carried out, each using a different set of input hypothesis. For the proposed area, the HOMER model was utilized to construct and analyze the most efficient hybrid renewable energy systems. The solar resource of the researched area was assessed in the first part of the research. The component parameters, such as inverter and battery sizes and costs, were then imported to HOMER software using the monthly solar profile, load demand values, economic constraints such as interest rate and project lifetime, and other related information. Following an optimization analysis of the various optimum hybrid energy configurations, HOMER recommended the most cost-effective and efficient hybrid energy combinations based on total net present cost of the system and electricity generation.

2.2 Net Present Cost (NPC)

The total Net Present Cost (NPC) is the quantity used to describe the system's life-cycle cost. All costs and revenues that occur during the project's lifetime are included in this single value, with future cash flows discounted to the present. The initial capital cost of the system components, the cost of any component replacements that occur during the project lifetime, the cost of maintenance, and the cost of fuel are all included in the total net present cost. The formula used to calculate the system's net present value is given as:

$$NPC = -C_o + (B - C)\sum_{E=1}^{T}\left([1+| {}^{d}/_{100} |]^{-6} + L_T[1 + | {}^{d}/_{100}]^{-6}\right) \quad (1)$$

Where Co is the initial investment, B denotes the annual benefits, C represents the annual investment, d represents the discount rate, t is the time. The project with the highest positive NPC is the most economically feasible of the mutually exclusive events.

III. CASE STUDY LOCATION

The study presents a feasibility study of PV/diesel hybrid system to supply FM village of Maitumbi, Niger, Nigeria. The case study is a rural area. There is a main health center and a primary school in the neighborhood. Every home has a lingthing point, as well as a television, a fan, and a radio. The study area was chosen to promote distributed generation, alternative energy systems, and renewable energy. Figure 2 shows the daily load profile of FM village in Maitumbi, Niger State, Nigeria.

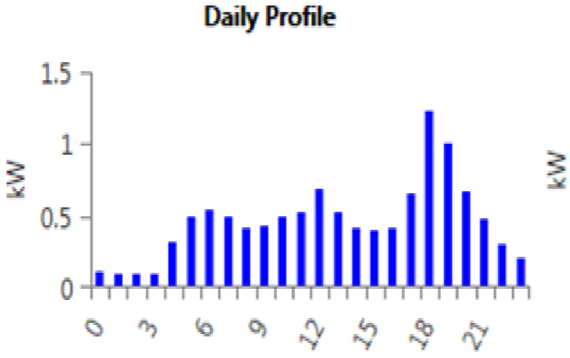

Figure 2: Load profile of 50 houses in FM village Maitumbi, Niger, Nigeria. (HOMER 2022)

From the load profile in Figure 2, it can be observed that the peak load hour was between 19:00 – 20:00 hour due to many activities taken place such as lighting and watching TV etc., the base load was between 23:00 – 06:00 hours due to less used of appliances as it is usually the time to rest or sleep. After inserting the load (kW) at each hour in a day, HOMER simulator software generate a scaled annual average demand of the case study as 140.19kWh/day which is the same as 51.1694MWh/year. The load type, wattage, usage hours and energy consumption of one house is depicted in Tables below

Table 3.1a: Energy consumption of Maitumbi FM village in Minna, Niger state.

Appliances	No in use	Wattage	Usage hours	0	1	2	3	4	5	6	7	8
Lighting point	5	20	12	1200	1200	1200	1200	1200	1200	1200	0	0
Television	2	80	4	0	0	0	0	0	0	0	0	0
Fan	3	30	12	1620	1620	1620	1620	1620	1620	0	0	0
Radio	1	12	8	0	0	0	0	0	0	0	0	0
Energy consumption per hour				1.23	1.23	1.23	1.23	1.23	1.23	1.2	0	0
Energy consumption for 50 houses				61.5	61.5	61.5	61.5	61.5	61.5	60	0	0

Table 3.1b: Energy consumption of Maitumbi FM village in Minna, Niger state.

Appliances	9	10	11	12	13	14	15	16	17	18	19	20	21	22	22	23
Lighting point	0	0	0	0	0	0	0	0	0	0	1200	1200	1200	1200	1200	1200
Television	0	0	0	0	0	0	0	0	0	0	640	640	640	640	0	0
Fan	0	0	0	0	0	0	0	0	0	0	1620	1620	1620	1620	1620	1620

Radio	96	96	96	96	0	0	0	0	0	0	96	96	96	0	0	0
Energy consumption per hour	96	96	96	96	0	0	0	0	0	0	1322	1322	1322	1310	1230	1230
Energy consumption for 50 houses	0.096	0.096	0.096	0.096	0	0	0	0	0	0	1.32	1.32	1.32	1.31	1.23	1.23

Table 3.2a: Energy consumption of Health care center/Primary school in Maitumbi FM village Minna, Niger state.

Appliances	No in use	Wattage	Usage hours	0	1	2	3	4	5	6	7	8
Lighting point	6	20	12	1400	1400	1400	1400	1400	1400	1400	0	0
Television	2	80	4	0	0	0	0	0	0	0	0	0
Fan	11	30	10	0	0	0	0	0	0	0	0	0
Refrigerator	1	600	4	0	0	0	0	0	0	0	0	0
Lighting	12	20	5	1200	1200	1200	1200	1200	1200	1200	0	0
Fan	0	0	0	0	0	0	0	0	0	0	0	0
Total Energy consumption per hour				2.6	2.6	2.6	2.6	2.6	2.6	2.6	0	0

Table 3.2b: Energy consumption of Health care center/Primary school in Maitumbi FM village Minna, Niger state.

Appliances	9	10	11	12	13	14	15	16	17	18	19	20	21	22	22	23
Lighting point	0	0	0	0	0	0	0	0	0	0	1400	1400	1400	1400	1400	1400
Television	0	0	4800	4800	4800	4800	0	0	0	0	0	0	0	0	0	0
Fan	0	0	3300	3300	3300	3300	3300	3300	3300	3300	3300	0	0	0	0	0
Refri	0	0	2400	2400	2400	2400	0	0	0	0	0	0	0	0	0	0
Lighting	0	0	0	0	0	0	0	0	0	0	1200	1200	1200	1200	1200	1200
Fan	0	0	0	0	0	0	0	0	0	0		0	0	0	0	0
Total Energy consumption per hour	0	0	10.5	10.5	10.5	10.5	3.3	3.3	3.3	3.3	2.6	2.6	2.6	2.6	2.6	2.6

3.1 Solar GHI resources

The case study has a latitude of 9º40.6 N and longitude of 6º32.2E. The case study's solar GHI resource was obtained online from NASA's surface meteorology and solar energy resource directory. From the downloaded data, the months, clearness index, daily radiation, and a bar chart are displayed. The study has a GHI of 5.49 kWh/m^2/day on an annual basis, which is sufficient for solar PV installation. Figure 3 shows that the area receives high solar radiation from February to June due to the hot season, whereas December and August receive low solar radiation due to the severe winter and heavy rainfall, respectively.

Figure 3: The annual solar radiation and the clearness index for the location of Niger, Nigeria (HOMER, 2022).

3.2 Inverter Model

The inverter is chosen in accordance with the capacity of PV array. As a result, a 24kW inverter was suggested in order to convert the photovoltaic module's maximum output completely. However, because the output of the solar module varies with the amount of sunlight, the converter's capacity was set to 100% and the overall efficiency was specified by the manufacturer as 97.5 percent.

3.3 Battery Model

Battery sizing is critical for designing a reliable off-grid system. When sizing a battery bank, the basic goal is to install the right amount of batteries to carry a specific load during a period when the sun or wind aren't available. The Lead Acid 12V type was chosen as the battery storage for the design. This battery was made to support renewable energy systems with high daily loads, and its enormous ampere-hour capacity makes it perfect for large off-grid photovoltaic (PV) installations. It also complied with both IEC and BCI standards. The battery has a nominal capacity of 83.4A-H and the optimal configuration was chosen from the optimization results given by the HOMER software based on operating cost and total Net Present Value (NPC).

3.4 Diesel Generator

The generator, often known as gen-sets, is another crucial component of an off-grid system that is utilized to charge batteries during periods of low insolation. Because the duration of sunshine tends to decrease during the rainy season, a diesel power generator set was included in the design as an overall backup and as a supplementary energy source on days when the solar irradiance is low. As a result, a Cummins diesel-powered generator was chosen for this project. The chosen generator has a power rating of 25kW to meet peak load demand, with an excess of 7kW (28%) serving as a spinning reserve in the event of future load increases. When the designed storage battery bank is unable to meet the energy requirement, the generator was installed to provide backup power.

3.5 Operation Strategy

The proposed energy system is considered to function using a load-following dispatch approach, which allows the generator to produce only the amount of energy required to meet the load requirement. This means that the photovoltaic system will always be in charge of charging the battery bank, and that anytime the generator is compelled to function, it will only provide enough energy to meet the load's energy requirements. The system's proposed configuration is presented in Figure 8. The inverter converts the PV array from DC to AC once it has been rectified by the rectifier, according to a brief explanation of this system. Because there will be excess power generation from the PV, the batteries will be charged as soon as the sun rises each day.

IV. RESULTS AND DISCUSSIONS

Renewable energy systems provide a remedy to over-dependence on fuel by reducing dangerous carbon waste produced by fossil fuel combustion and, as a result, improving the atmosphere by making it cleaner. The high capital cost of incorporating solar energy into a design is one of the reasons for its low penetration in global electricity generating. However, as has been witnessed over time, continuing research and development in this field would substantially reduce manufacturing costs. As previously stated, numerous system configurations were explored in this study during the sensitivity analysis for the simulation as previously discussed, in order to establish the most optimum design combination.

As HOMER has significant optimizing functions, it may be used to determine the cost of various project scenarios by applying the functionality for cost minimization and optimization of predicted energy system design based on a variety of parameters such as cost and CO_2 reduction, among others. Different capable energy system topologies are presented to meet these goals, along with their financial implications (as shown in Table 4.1). The cost-effectiveness of our proposed energy system was next considered, as well as the reduction of hazardous emissions.

4.1 Standalone PV System

This study will look into the potential of constructing a standalone PV system due to the diesel generator's harmful gas emissions. Despite the high cost of PV modules and batteries, it achieves 100% renewable energy penetration when compared to standalone diesel, PV-diesel without battery, and PV-diesel with battery configurations. Figure 4 depicts a schematic model of a standalone PV system.

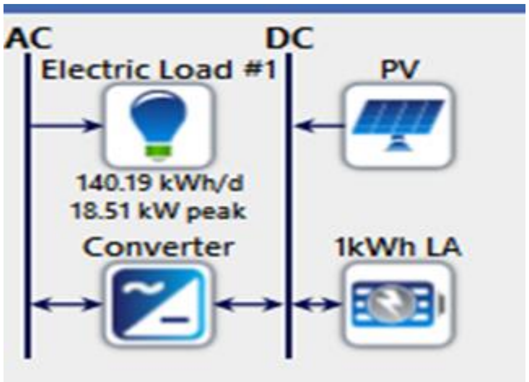

Figure 4: The schematic diagram of standalone PV system (HOMER, 2022).

The standalone PV configuration, when compared to the rest of the standalone diesel, PV-diesel without battery, and PV-diesel with battery configurations, has the largest extra electricity of 81.3 percent. It has the most capital, with a PV module costing $159,219.85, a battery costing $293,152.96, and a power conditioning unit costing $9,653.76. One of its benefits is that no gases are released. Figure 5 depicts the net present cost of a solo PV system.

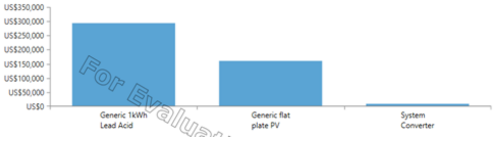

Figure 5: The Net Present Cost summary of Standalone PV system (HOMER, 2020)

The cost of electricity was computed to be $0.699/kWh which is higher than the standalone diesel system. Operating and maintenance cost is $13,356 which is less than the configuration of standalone diesel system. Another advantage of this configuration is no issue with fuel price. Due to oil crisis worldwide, the fuel price is unstable from time to time.

4.2 Standalone Diesel Base System

The capacity of the diesel generator should be equal to the electric power's peak demand. In order to meet the peak load requirement of 18.51kW, a 25kW diesel generator was considered in this research. The peak demand of 18.51kW was calculated by taking into account the many types of loads found throughout the village, as well as the wattage, usage hours, and energy consumption of each residence, primary health center, and primary school. The spinning reserve was 6.5kW. At a diesel price of 0.5 $/L, the generator's annual operating costs were estimated to be $31,914.93/year, with a levelized cost of energy (COE) of 0.6396 $/kW and a net present cost (NPC) of $423,080.70. The generator has a 15,000-hour operating life expectancy. The configuration is depicted in a schematic figure.

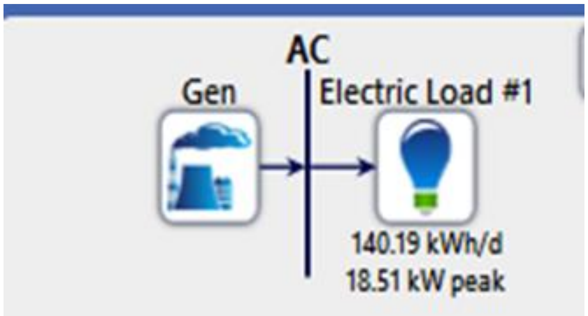

Figure 6: The systematic diagram of the standalone diesel system (HOMER, 2022)

4.3 Hybrid PV-Diesel without Battery System

The simulation results based on the system configuration, the optimum configuration is 24kW PV array, 25kW diesel generator, and 24kW converter, which has the lowest net present value NPV and cost of energy COE of $424,425 and $0.642/kWh, respectively. Figure 7 depicts a systematic diagram of a hybrid PV/diesel system without a battery.

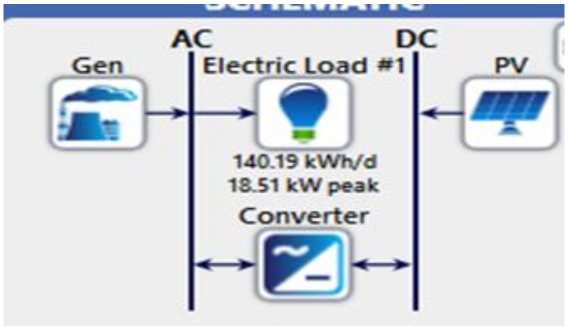

Figure7 The systematic diagram of the hybrid PV/diesel without battery (HOMER 2022)

The surplus electricity is 42.3 percent, which is lower than the PV/battery combination. Due to the presence of a battery in the PV/battery system, the excess electricity generated by the PV is usually minimized. In some hours, the battery used a portion of the excess electricity to charge and supplement the load. Renewable energy penetration was low in this area. However, as seen in Figure 7, the emissions are higher with the battery combination than with PV/diesel.

4.4 Hybrid PV-Diesel-Battery System

Table 1 shows the results of the sensitivity analysis of the hybrid PV-diesel system with battery storage element. In this scenario, the impact of battery storage on the proposed hybrid power system was explored. A PV array with a capacity of 24 kW, a diesel generator with a capacity of 25 kW, and 24 kW of batteries make up the entire system. Figure 8 depicts a schematic illustration of the system configuration.

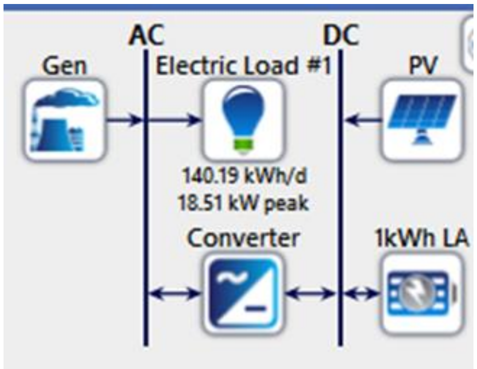

Figure 8: The systematic diagram of the hybrid PV/diesel with battery (HOMER, 2022)

Table 4.2 illustrates the hybrid PV/diesel with battery storage has a total NPC of $324,427.90, indicating that adding battery storage to the previous configuration system reduced the total net present cost even though the addition of battery increased the total capital and replacement cost, resulting in an annual cost of operation reduction of $19.092.03/year. As a result, the total NPC of this system configuration has been decreased from $423,080.70 in the no-battery design stated to $324,427.90. Furthermore, the proposed system's renewable penetration was found to be 49.2 percent higher than PV/diesel without battery configuration.

Table 4.1: Sensitivity analysis result of PV-Diesel-Battery Systeme

PV (kW)	Gen(kW)	Battery (Units)	Converteter (kW)	COE ($/kwh)	Total NPC ($)	Operating Cost ($/yr)	Initial Cost ($)	Ren Frac	Gen (Hours)	Diesel (L)
24	25	56	24	0.490	324,428	19,093	77,604	36.9	2.763	10,857
24	25	58	24	0.491	324,675	18.968	79,461	37.6	2,691	10.687
24	25	56	24	0.491	324,694	19,178	76,769	36.6	2,792	10,935
24	25	57	24	0.491	324,711	18,993	79,178	37.4	2,721	10,747

Table 4.2: System components operation results and pollutant emissions for PV–diesel– battery system.

Quantiy	Value	Unit
Battery		
Engergy in	14,168	kWh/year
Energy out	11,341	kWh/year
Losses	2,834	kWh/year

Annual througtput	12,679	kWh/year
Expected life	3.53	Year
Diesel generator		
Hours of operation	2,763	hrs/year
Number of start	1,060	starts/year
Operational life	5.43	Year
Marginal generation cost	0.236	US$/kWh
Electrical production	32,267	kWh/yr
Mean electrical output	11.7	kW
Max. electrical output	21.0	kW
Fuel comsuption	10,857	L/year
Pollitant		
Carbon dioxide	28,420	kg/year
Carbon monoxide	179	kg/year
Unburned hydrocarbon	7.82	kg/year
Particle matter	1.09	kg/year
Sulfur dioxide	69.6	kg/year
Nitrogen	168	kg/year

The proposed hyrid systems' PV array generates 31,299 kWh of electrical energy per year. In this configuration, some of the surplus electricity is stored in batteries, which are then used whenever the need arises, resulting in an increase in the proposed system's renewable energy penetration. Furthermore, the PV array's generated power contributed more to the supplying demand than PV/diesel without batteries, reducing the requirement for the generator and, as a result, the penetration of non-renewable sources for electricity generation.

The batteries produced electrical energy at a rate of 12,679 kWh per year. The PV array is charged by battery bank, therefore, the PV array and the batteries concurrently produced 49.2% of the electricity generation from the system which is also the total renewable generation (fraction) from the entire system. The diesel generator being one of the major component of the system, it is operated for 2,763 hours per year and consumes a diesel of 10,857 L/year to produce 32,267 kWh (50.8%) of electrical energy per year which is the remainnig percent of the whole power generation.

Initially, it is noted that the inclusion of a battery to the arrangement has greatly decreased carbon dioxide emissions in the proposed system, owing to the diesel generator's reduced hours of operation. Figure 9 compares the CO2 emissions and renewable penetration of PV/diesel without battery, standalone PV system, PV/diesel with battery, and diesel generator.

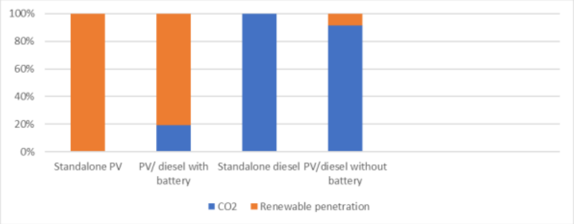

Figure 9: Comparison of four configuration system based on excess electricity, CO2 emission and renewable energy penetration.

CONCLUSION

This study investigated four distinct configurations, including the traditional diesel generator, PV-battery, PV-diesel, and PV-diesel-battery configurations. For the sensitivity analysis, a hybrid optimization model for electric renewables (Homer) was applied. The net present cost, renewable penetration, and carbon dioxide emission as factors for establishing the optimal system configuration are the main emphasis of this study. A PV-diesel-battery hybrid power system (HPS) was recommended for the village under consideration at the conclusion of the study. The system consists of a 24 kW solar array, a 25 kW diesel engine, 56 battery units, and a 24 kW power converter that generates 63,566 kWh per year, with 49.2 percent renewable energy. For a 25-year life span and a 10% annual interest rate, the system NPC is $324,427.90. As a conclusion, taking into account the geography and location of the case study, which is located within the town of Niger state. Hybrid PV/diesel with battery was suitable for that area so as to reduce the use of standalone diesel generator and to promote the use of alternative energy sources.

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