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Energy Storage Solutions for Enhanced Performance in Off-Grid Solar Systems in Abuja: Nigeria

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Abstract

Over the past decade, there has been a discernible increase in the need for energy, mainly due to the widespread expansion of the industrial sector and population development. Nigeria needs a lot of energy resources to be sustainable because of its large population. As a result, there is now a significant reliance on natural gas and crude oil for energy, which makes us vulnerable to shortages of these supplies. This dependence has negative effects on the country's economy and climate change. In light of these difficulties and the limited supply of fossil fuels as well as its negative effects on the environment, there is a global movement to use sustainable energy resources and technologies to meet the increased demand for energy. In the field of renewable energy technology, solar photovoltaic (PV) systems have become a viable option. An enduring, sustainable, and environmentally beneficial energy source for the future is offered by these systems, which directly harvest solar radiation from the sun to create electricity. Photovoltaic devices are a suitable sustainable energy alternative because of their ecological and economic advantages. This makes them compatible with international initiatives such as Sustainable Development Goal 7 (SDG-7), which aims to guarantee that everyone has access to modern, affordable, dependable, and sustainable energy. In particular, this study explores whether it would be feasible to install an off-grid photovoltaic system in Abuja, Nigeria, which is located at latitude 9°03'28" N and longitude 7°29'20" E, to meet the electrical needs of a residential building. The inquiry investigates the PV system's total capacity to meet residential power consumption, using a mathematical modeling methodology for both design and analysis. The results obtained from the use of mathematical modeling methodology indicate that ten MLE275HD2 PV modules, with a capacity of 285 Wp apiece, when combined with five 100 Ah batteries, can effectively handle a requirement for electricity throughout the year of about 3123 kWh.

Keywords

Solar energy, Photovoltaic, Energy, Renewable energy, Solar radiation, PV panels, Peak PV power, Homesteads, Abuja, Nigeria

1. Introduction

Nigeria, a country with over 192.0 million people, can only provide electricity to about 50% of its population despite having abundant fossil fuel reserves and the potential for renewable energy sources like hydro, wind, biomass, and solar energy [1]–[3]. Given their vast potential, renewable energy sources offer a solution to the world's energy security problems and contribute to reducing carbon emissions [4]. Numerous studies have examined how easily residential homes can obtain modern energy services, taking into account availability, affordability, and the accessibility of the household to the power grid and utility suppliers [5], [6]. The country's electricity accessibility rate is compromised by the issues faced by the power sector, which include administrative and technical shortcomings [7], [8]. Despite the fact that certain energy consumers in the downstream sector rely on generators to supply electricity, the high running costs of this strategy make it unsustainable [1]. Solar-powered electricity can be used to meet local energy needs and enable small-scale electrification projects like traffic and street lighting, making it a more sustainable approach to expanding access to electric power [9], [10]. The most accurate method to use solar energy, which is renewable and ecofriendly, is to install solar photovoltaic (PV) systems, which transform solar radiation directly into electrical energy [4], [11]. A key component of micro-grid power generation, which includes rooftop renewable power by private households, is the photovoltaic system [12]. In addition, solar photovoltaic energy has the capacity to support economic expansion and meet the electrical needs of rural locations.

Nigeria's daily worldwide horizontal radiation ranges between 4.8 kWh/m2/day (26.5 MJ/m2/day) and 7.0 kWh/m2/day (15.7 MJ/m2/day), with an average daily solar irradiation of 7.5 hours. [13] The case study location is located in the north-central portion of Abuja, at latitude 9°03'28" N and longitude 7°29'20" E. It receives 8 hours of sunshine per day. According to [8], [14] Nigeria has a worldwide horizontally oriented irradiance of 228 W/m2, and Abuja has an ideal wind velocity of about 9.77 m/s, which is significantly higher than the 6.5 to 9.5 m/s wind speed in the north. The example study location experiences solar irradiation ranging from 5.2 to 5.8 kW/m2/day. Furthermore, it has been determined that the average yearly daily solar energy intake (Havg) for a south-facing, inclined terrain at Latitude 9.8^{O} in Abuja is 6.855 kWh/m2.Furthermore, it has been determined that the average yearly daily solar energy intake (Havg) for a south-facing, inclined terrain at Latitude 9.8^{O} in Abuja is 6.855 kWh/m2. Meteorological conditions and topography, solar radiation is essential for producing power. Figure 1 shows a map of Nigeria's solar radiation with an emphasis on Abuja. Fig. 2 displays the monthly average of the average daily global radiation from the sun for Abuja, Nigeria, based on [2]. It is expected that variations in monthly global sun radiation will cause the off-grid PV system's energy output to fluctuate. It is anticipated that power generation in March, April, and May will surpass that of previous months [1], [15].

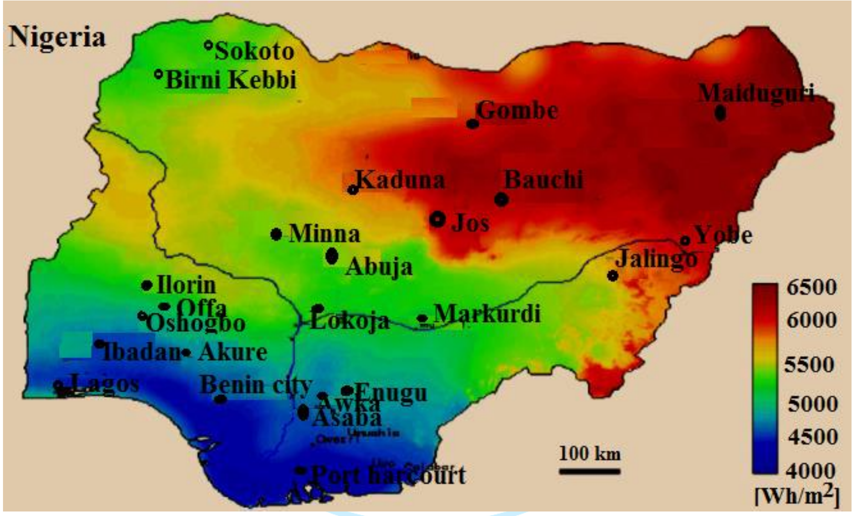

Fig.1 The map showing Nigeria's sun radiation. [2]

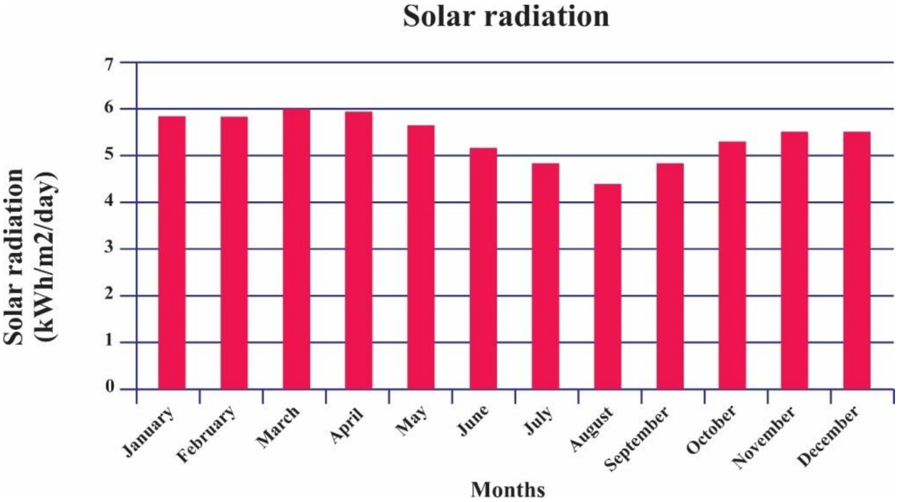

Fig. 2 The accessed solar energy chart for Abuja, Nigeria

Diverse sizing techniques and techno-economic models are applied worldwide to ascertain the appropriate dimensions for standalone and hybrid solar PV systems [16]–[18] examined five tracking modes while closely examining the 2.04 KWp standalone solar PV system's performance using the PVSYST V5.75 software. According to the results, a predetermined tilt angle of 25 degrees provided the least amount of solar energy supplied (2463 KWh/y), while the dual-axis tracking system produced the largest amount (3071 KWh/y) [19]. Utilized a sizing technique that incorporated the levelized cost of given and unused energy to investigate standalone rural power in Uganda. PV modules, batteries, inverter cost, operating and maintenance costs, and other elements are included in the size criteria. Although the authors' sizing method took into account the electrical requirements of remote places in poor nations, it did not address the metric's suitability for supplying electricity to cities. [2], [5] conducted a techno-economic analysis for a condominiums residence in a portion of China, comparing an autonomous hybrid diesel battery and a solar battery using the RETScreen tool. Analysis and comparison were done on fixed, one-axis, and two-axis solar tracking options. Fixed-tilt array solar tracking was out to be less successful at catching solar radiation, but it was more affordable than one- and two-axis tracking options. An off-grid PV-battery system employing two-axis tracking technology had a higher cost of energy (COE) than the fixed-tilt array PV-diesel-battery system, according to the authors' comparative analysis of the costs related to greenhouse gas (GHG) reduction. Additionally, in comparison to the off-grid PV-battery system with the two-axis tracking system, the PV-diesel-battery system demonstrated the greatest cost reduction. However, information about the COE and GHG of the off-grid PV system was absent from the study. A stand-alone photovoltaic system was investigated by [5], [20], [21] with an emphasis on planning, technical frameworks, modeling, and optimization methodologies. The authors looked into the importance of optimal sizing in achieving the lowest system cost. They came to the conclusion that models based on reliability are essential for evaluating how well hybrid renewable energy systems operate. In order to minimize costs while satisfying the needs of home electrical loads, [22] conducted a techno-economic analysis of a hybrid freestanding diesel, PV, and battery generator for Malaysian remote residential buildings. The importance of such efforts is demonstrated by this study. The combination of PV modules, battery system, and diesel generator provided the lowest COE of $0.249/kWh when the PV contributed 90% and there were 0.4 autonomous days, according to the authors' mathematical modelling. Furthermore, in comparison to PV grid-connected solar, the 140 percent PV contribution had zero emissions and a COE of $0.319/kWh. The plant that produced diesel, batteries, and photovoltaics hybrids was mainly economical, but it also greatly increased CO2 emissions. The goal of [23] aimed to attract investment into the German, Swiss, and Austrian residential and commercial building sectors by evaluating the techno-economic performance of a rooftop photovoltaic self-consumption system without financial assistance. The substantial difficulties with rooftop photovoltaics and the self-consumption system were also discussed by the writers. The Home Model for Intelligent Energy, or HOMIE, model was also used by the authors to perform comparative analyses, with the main components being techno-economic data, climate variables, and energy consumption. The data indicated that the rooftop PV system was financially sustainable based on the building's self-consumption share and electrical energy rates.

The ability of self-sufficient solar home systems to provide rural people in developing countries with power has been the subject of numerous studies. Examining self-sufficient electrical energy using solar dwelling technologies (SHT), [18], [24], [25] focused on the solar component, battery system, charge regulator, and power inverter. The practical examination revealed that these components from various producers did not meet national and international standards. Despite the writers' enthusiastic affirmations, it was unclear whether customers of self-sufficient electrical energy were aware of the SHT component quality. Using the RET-Screen software, [26] did a techno-economic investigation in Coatzacoalcos, Mexico. They found that 16 units, each rated at 324 W, could produce 5.61 MWh, reducing greenhouse gas emissions by 11 tCO2, with an average daily sun irradiation of 5.5 kWh/m2. The area of the PV modules was not mentioned, though [27] investigated the techno-economic elements of roofing solar systems in the domestic, business, and factories domains, with a particular emphasis on Karnataka's current policy. The investigation emphasized the industrial rooftop photovoltaic system's better economic viability, which is attributed to its ability to generate certificates of renewable energy and impact the commercial sector. The inability of home off-grid systems to make money from electricity generated a correlation with their non-economic viability. Numerous studies have employed analytical software, such as the HOMER (Hybrid Optimisation Model for Electric Renewables) programme, to assess the techno-economic viability of off-grid solar power stations. [28]. For health centers and a school, [22] PV socio-technical statistics was analysed to find solutions for improving battery longevity and system dependability. The authors performed sociological and technical assessments of PV performance, including cost comparisons between PV and diesel systems, using MATLAB as the modeling tools as well. The authors came to the conclusion that battery degradation could be lessened by putting socio-technical measures in place. Table 1 unveils an overview of the diverse approaches employed around the world.

The deployment of both interconnected and standalone solar photovoltaic (PV) systems for power generation has been the subject of numerous investigations in this nation [12], [29]–[32]. This research used the HOMER programme to assess the sustainability of an interconnected solar photovoltaic (PV) system for energy generation in Abuja, Nigeria. The author's analysis focused on solar photovoltaics (PV) and sun irradiation, and revealed that the networked PV system can provide up to 40% of the total power. The levelized cost of energy and expected annual electrical energy were calculated to be 333,546 kWh and $0.105/kWh, respectively. The study did not, however, account for the challenges of implementing a PV system into the power grid, the limitations of current grid infrastructure, configuration as well as transmission costs, the state of monitoring technology at the time, or the level of experience required to implement an interconnected solar PV system. [33], [34] investigated the possibility of utilizing HOMER to install a solar PV-diesel-battery hybrid system in Abuja, Northern Nigeria. After taking into account two rated power options for the diesel generator and ten various PV capacities, the study came to the conclusion that the hybrid PV-diesel-battery system produced electrical energy at a lower cost than a solo diesel generator. Using the HOMER program, [23], [35] we reproduced an off-grid PV system for an office block in North-West Nigeria, dividing the investigation into two portions using well-known electrical gadgets. Based on the average energy consumption of 36.35 kWh per day, Category 1 was found to be more economical than Category 2, which had an average energy consumption of 199.1 kWh per day. Furthermore, using the RET-Screen program, [1] carried out a life-cycle cost analysis to assess the feasibility of installing an off-grid PV system in North-Eastern Nigeria.

The overall cost of an independent photovoltaic (PV) system was calculated by the researchers using a life-span gauge, and the results were compared to the cost of the existing electrical grid. Their concluding analysis, which focused on elements like incentive programs, regulatory frameworks, and legal frameworks, showed the practicality of a freestanding photovoltaic system. Nevertheless, important information was omitted, such as the particular costs associated with off-grid photovoltaic systems and their ecological advantages. [2], [36] conducted a techno-economic assessment of a hybrid photovoltaic-diesel-battery system for an international college in Northern Nigeria using the HOMER program. The power plant, charge controller, converters, and PV panels were all considered. The findings demonstrated that in order to meet the institution's 105 kWp power consumption, a PV peak output of 120 kWp required a module area of 982 m2 and two batteries (1256 Ah, 12V). Compared to off-grid diesel-powered power facilities, the hybrid PV-diesel-battery system reduced CO2 emissions by 8487 kg/year at a cost of electricity (COE) of $0.568/kWh. In Kastina, Northern Nigeria, four topologies were assessed for the COE using HOMER software in a different study effort [15]: Off-grid solar photovoltaic self-sufficient diesel generation plant, Photovoltaic-diesel battery, and Photovoltaic-diesel system. According to the findings, the PV-diesel-battery system with the lowest COE was chosen. Although earlier studies have examined the advantages of linked photovoltaic systems and the possibility of photovoltaic hybrid technologies in Abuja, Nigeria, there is a gap in our understanding of how feasible it is to install PV systems for self-sufficient power requirements. By assessing the feasibility of creating an off-grid photovoltaic system for home power generation while accounting for the region's abundant UV radiation and households' modest energy requirements, this study seeks to close this gap. The installation of various PV hybrid systems, as well as the removal of environmental and regulatory issues, are the main foci of the paper, which use a computer modeling approach to examine techno-economic feasibility. The characteristics of solar radiation exposure, PV peak power, inverter size, battery size, and charge controller were determined for this study.

2 Methodology

2.1 Data Collection

Prior to developing an off-grid solar system that produces power for the home, the electrical needs of the residence must be evaluated. The authors employed the technique outlined by [37] to undertake a thorough investigation into the technical and economical elements of solar PV systems. The technological and economic evaluation begins with data gathering and appliance utilization analysis in a three-bedroom home with six people. Selecting between permanent appliances and adaptable, planned, or shiftable loads based on how long they operate for is one phase in the classification process [38][39]. The equation includes the number of the consumer appliances ranging their power assessment, hours of operation, average daily energy usage, and the solar PV system's technical characteristics. The commercial viability of solar PV systems is then assessed using measures such as the cost of energy (COE), annualized levelled cost (ALLC), and levelled cost (LLC). The phases of the approach are described here, with an illustration of the process provided in Fig. 3.

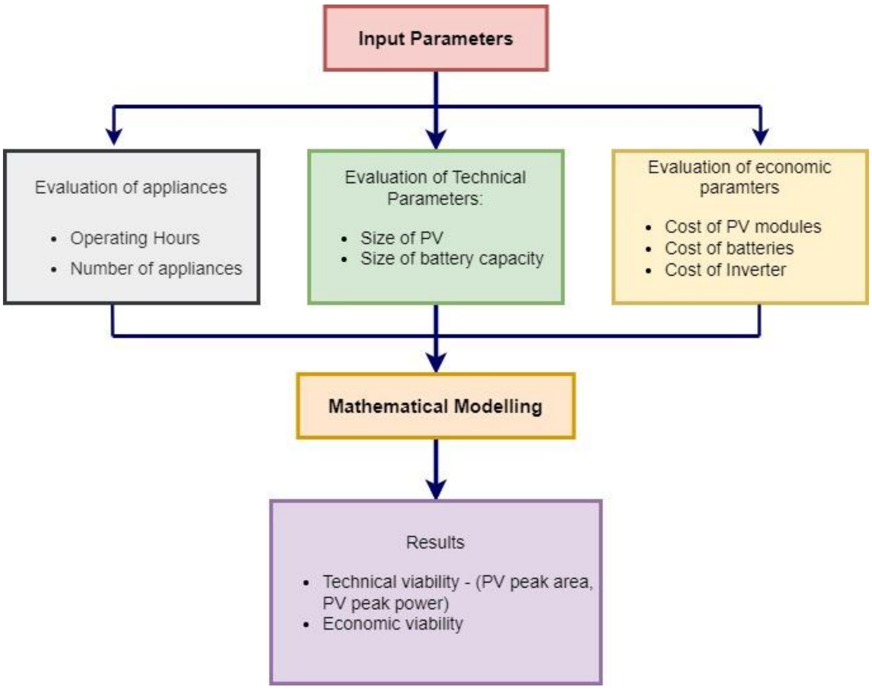

Fig.2. Measures taken while conducting the techno-economic evaluation of solar photovoltaic (PV) panels [2]

2.2 The Evaluation of Appliances Owned By End Users

The method used to analyze the data collected is computational modeling. As Table 1 shows, a number of studies have demonstrated the utility of using numerical modeling to assess the techno-economic potential of solar power technology. The case study is not a complex mechanism, therefore using mathematical modeling is justified for the research's explication and insight goals. As the technical and economic statistics in this method are not based solely on data from satellites for evaluation, nor are they numerically generated like in the HOMER software program, correct results are guaranteed [12]. Application of mathematical modeling accounts for the amount of solar energy per unit area and the electricity demands in the case study location. Consequently, the computations shown below are done:

This mathematical formula calculates each electrical appliance's average daily electricity consumption. eq. (1):

$$A_{ei} = \sum nip \text{ , (kW)} \tag{1}$$

Knowing that;

A_{el}	Average amount of power used each day (kWh/day)
i	the kind of electrical appliance charge.
n	quantity of the electrical appliance charge.
p	electrical load's power assessing. (W)
h	typical working hour

2.3 PV Parameters Sizes

Effective PV array modelling takes into account both the starting daily electricity consumption and the daily solar energy generation in kWh m -2 d-1 in order to meet the average daily power requirements of a residential building. The needed area of the PV array is the predominant variable that has to be taken into account. The energy created by electrical consumption (kWh), daily solar electricity production (kW HM-2 d-1), photovoltaic module efficacy percentage, and module thermal coefficient (TC), also referred to as the correction factor, are the factors that determine this. Table 3 provides a list of the PV module specs used in this investigation, considering a temperature correction factor (TCF) of 80% to account for the reduction in efficiency owing to a temperature increase up to 60°C. Equation (2) [40] is used to compute the aggregate PV array area (APV) based on these factors, and Equation (3) [13] is used to estimate the PV peak power.

(a) The following formula is used to get the average photovoltaic array area.: Equation (2)

$$A_{PV} = \frac{El}{HXTC \; x \; \eta PV \; x \; \eta \mathrm{l\,nv} \; \mathrm{x} \; \eta \mathrm{B}} \; (\mathrm{m}^2) \tag{2}$$

Knowing that;

H	daily cumulative solar radiation (kWh/m^2 day)
Tc	coefficient of thermal conductivity (assumed at 80%)
ɳPV	performance of PV modules (assumed to be 15.5 %)
ɳlnv	the inverter's precision (assumed to 85 %)
ɳB	battery life (presumed to be 90 %)

(b) Pp(PV), the peak power of the PV array, is evaluated using Equation. (3).

$$Pp_{(PV)} = A_{PV\ x\ lp\ x\ \eta_{PV,}} \; (W) \tag{3}$$

Knowing that;

A_{PV}	the typical area of a PV array (m^2)
I_P	the sun's maximum intensity as 1000 W/m^2.

2.4 The Size of the Power Supply System

The sun's energy is irregular and has a limited daily duration, so designing the battery system carefully is necessary for several reasons, such as promoting sustainable development in the production of power and enabling energy storage [6]. The number of cloudy or autonomous days, battery performance, inverter performance, depth of discharge (DOD), and the amount of the electrical load(s) are therefore taken into consideration in the design of the battery system. Equation (4) demonstrates how battery memory capacity is represented mathematically. The battery's storage capacity was assessed using a DC bus voltage of 24 V in order to minimise system losses.

$$B_{SC} = \frac{EL \; x \; NCC}{Dd \; x \; \eta lnv \; x \; \eta B} \; (Wh) \tag{4}$$

Knowing that;

B_{SC}	The storage capacity of the battery (Wh)
N_{CC}	The number of days with cloud cover (0.8)
Dd	Depth of discharge (estimated at 85%)
E_L,	ɳinv, ɳBas previously mentioned

2.5 Charge Controller Sizing

After that, we design a charge controller that takes into account the photovoltaic (PV) array current, solar power plant voltage, and battery storage unit voltage in order to help the off-grid system's batteries operate more efficiently. The charge control device is made to synchronise at least 28% of the maximum solar photovoltaic array capacity in order to compensate for low conditions. The control unit, which includes a maximum power point tracker (MPPT), is designed to activate the battery charging system and then stop charging at a predefined maximum voltage. To allow rechargeable batteries, it also stops the charging mechanism at a preset low voltage. [13], [25]. The MPPT controls the flow of current into and out of the battery system, preventing excessive charging and overloading of the battery's power supply. Additionally, the system of batteries voltage and the solar PV module voltage are both intended to be met by the charge controller. Its responsibilities involve assessing the quality of the charging of the battery system and the performance of the solar PV array, influencing the power utilized by electrical loads, and improving the lifespan of the batteries [29].

2.6 Monthly Production of Solar Photovoltaic Systems Inverter Sizing

Equation can be used to determine the monthly energy output potential for off-grid solar energy systems. (5) [16]. The monthly sunlight exposure from the laboratory study of [23] is used for estimating the monthly generation from a solar energy system. The authors chose a DC-AC inverter system in line with [41], [42] to fulfil the least 25% of the electrical loads needed by the end users.

$$M_{PV} = A_{PV}\ x\ \eta_{PV}\ x\ M_{irradiation},\ (kWh)/month \qquad (5)$$

Knowing that;

$M_{irradiation}$ the solar radiation per month ($kWh/m^2/day$).

2.7 PV System Economic Evaluations

A key modelling technique for analyzing the financial implications of renewable energy technologies is the life cycle cost evaluation, which covers all phases of the PV system life, from the initial capital investment or acquiring prices to continuous operation and maintenance costs. The expenses related to PV panels, storage systems, charge control devices, inverter systems, and installation are incorporated into the initial investment costs [10]. Costs associated with the maintenance and operation includes periodic upkeep, workplace monitoring, and yearly ongoing costs. The life cycle of the PV system is set at 25 years for this study, but additional elements, like as the system for storing energy, require regular servicing every 5 to 15 years. As a result, the 25-year lifespan of the PV system is used for the life cycle analysis. In this article, the rate of increase in inflation and discounting rate—which are presumed to be 8.1% and 10%, subsequently—are crucial variables in evaluating the life cycle expenses. A synopsis of the system's economic features may be seen in Table 4. To assess the cost of the PV array, initial battery cost, inverter cost, controller for charging cost, and installation cost, the numerical values given by [43] are used.

The cost of PV array Eq. 6 is used to determine the cost of the photovoltaic (PV) module, which is estimated to be USD 1.95/WP.

$$Total\ C_{PV} = Pp(pv) X\ USD\ \frac{1.95}{W_P},\ (US\$) \qquad (6)$$

Knowing that;

C_{PV} PV's price (US$)
$Pp(pv)$ PV maximum power in (W)

(1) The initial battery cost

Using the equation (7) below, the starting cost of the battery is calculated, assuming that its unit price is $2.2/Ah.

$$C_{iC} = B_{SC}\ x\ B_{UP}\ (US\$) \qquad (7)$$

Knowing that;

C_{IC} battery's starting cost, (US$)
B_{UP} The battery's unit cost, (US$)
B_{SC} has already been clarified

(2) Moreover, the batteries must be replaced every five years due to the battery system's five-year lifetime. According to [30]'s findings, the battery's present worth (PW) for the first, second, and third positions are, respectively, 5, 10, and 15. The PW (8) is computed using the equation.

$$C_{BI} = C_B \left(\frac{1+i}{1+d}\right)^N\ (US\$) \qquad (8)$$

Knowing that;

C_B Moreover, the batteries must be replaced every five years due to the battery system's five-year lifetime.

According to [30]'s findings, the battery's present worth (PW) for the first, second, and third positions are, respectively, 5, 10, and 15. The PW (8) is computed using the equation., (US$)

I	proportion of inflation (%)
D	proportion of discount (%)
N	battery life cycle Costs of charge controller lifetime (estimated at 5, 10, and 15 years, correspondingly)

(3) An inverter system's cost

It is expected that the unit cost is $0.32/WP based on [12], as demonstrated by the mathematical equation (9):

$$C_{iVN} = Cp \times Pp(pv),\ US\$ \tag{9}$$

Knowing that;

C_{inv}	Inverter costs, (US$)
C_p	The inverter's unit cost, (US$)
Pp(pv)	as previously described

(4) Charge controller costs

Equation shows that the cost of the charging system is calculated by multiplying its size by the unit cost. (10). The charge control system size in the present study is 120A, and the unit cost is $3.5/A.

$$C_{ch} = S_{cha} \times C_{uni}\ (US\$) \tag{10}$$

Knowing that;

C_{ch}	controller for charging costs, (US$)
S_{cha}	the charging controller's size
C_{uni}	the unit cost of charge controller (US$)

(5) The price of installation

The installation price, which is determined by applying Equation, is assumed to be 10% of the PV modules' initial cost (11),

$$I_{CPV} = 10\% \times I_{CPV},\ (US\$) \tag{11}$$

Knowing that;

I_{CPV}	initial PV cost, (US$)

(6) Cost of Maintenance

As stated in Eq. 12, the current study assumes that the expense for routine maintenance of the PV will be 2% of its initial cost. The 25-year life duration of the PV system, the 8.1 percent inflation rate, the 10 percent depreciation rate, and other factors are also taken into account in the PW of maintenance cost analysis (Cm). Using Eq. (13) [10], [40] and the following variables, the market price of Cm is determined: The solar PV system's lifespan, annual expenses for maintenance, 8.1 percent inflation rate, and 10 percent depreciation rate.

$$C_m = 2\% \times C_{ipv}\ (US\$) \tag{12}$$

Knowing that;

C_m	cost of upkeep
C_{iPV}	PV's initial cost

$$PWC_m = (M / yr) \left(\frac{1+i}{1+d}\right) \left(\frac{1-\frac{1+i}{1+d}N}{1-\frac{1+i}{1+d}}\right),\ (US\$) \tag{13}$$

Knowing that;

M	price of maintenance, (US$)
I	The rate of inflation, (%)
d	Ratio of Devaluation, (%)
N	length of time
Y_r	year
C_m	as mentioned earlier

(7) The expense that is levelized (LCC)

Total cost of the PV framework comprises of the Photovoltaic panels, batteries, PW of the power system, inverter, power converters, and installation. To represent the LCC, use equation (14) as given by [44].

$$LCC = C_{PV} + C_B + C_{B1} + C_{B2} + C_{B3} + C_i + C_C + C_m + C_{inst},\ (US\$) \tag{14}$$

Knowing that;

C_{PV}	PV's expense, (US$)
C_B	The battery's cost, (US$)
C_{B1}, C_{B2} & C_{B3}	5, 10, and 15 years' worth of battery cost, (US$)
C_i	Inverter costs, (US$)
C_C	the controller's charge costs, (US$)
C_m	maintenance costs, (US$)
C_{inst}	installation expenses, (US$)

(8) A life cycle cost that is annualised (ALCC)

The life cycle cost that is annualised is determined by taking into account a number of elements, including the levelized cost, project lifetime, inflation rate I, and discount rate (d). Using Equation (15) is the most effective way to evaluate the ALCC [5], [45].

$$\boldsymbol{ALCC = LCC\left(\frac{1-\frac{1+i}{1+d}N}{1-\frac{1+i}{1+d}}\right),\ (US\$)} \qquad \textbf{(15)}$$

Knowing that;

LCC leveled expenses, i,d,N are described previously

(9) The cost for electrical power per unit

The fiscal consideration determining the photovoltaic (PV) system's viability is the electricity generation unit cost (Uel). [42]. The cost of electrical energy is calculated by dividing the yearly total system cost by the total amount of electrical energy produced, as stated by [44]. Equation is used to calculate this ratio (16). [18], [46]. Table 4 provides a summary of the different expenses associated with off-grid photovoltaic systems.

$$\boldsymbol{U_{e1} = \frac{ALCC}{365lel}\ (US\$)/kW} \qquad \textbf{(16)}$$

Knowing that;

Energy cost annualized by ALCC

3. Result and Discussion

3.1 Outage Results of a Photovoltaic System off Grid

The core location of our case study, Abuja, Nigeria, is located between 9°03'28" N and 7°29'20" E. It receives a substantial amount of solar radiation year-round. The average daily irradiance, with an annual average sunshine length of 8 hours, is 5.66 kWh/m2/day. An off-grid photovoltaic system's design takes into account a number of factors, with the assumption that a temperature of 60 °C might result in a total correction factor (TCF) of 80 % and possibly as high as 14–20%. [47]. The authors assume that the battery productivity, inverter performance, and solar power performance are, respectively, 90%, 85%, and 15.5%. A 16.56 m2 PV array and 16.6% module functionality are required to produce enough electricity to meet the 8.58 kWh daily end-user load.

Table 1 An examination of the household appliances

Appliances	Quantity of appliances	Equipment power (W)	Total Power (W)	Working hours	Typical hours of operation (h)	Average amount of energy used each day (Wh)
Freezers	8	130	180	0-5	24	3360
Kitchen Stoves	2	40	120	9-12	5	640
Microwaves	5	30	140	19-24	1	300
Washing Machines	3	120	120	16-22	2	1000
Water Heaters	4	60	160	21-22	5	250
Blenders	2	60	120	0-24	0.5	200
Electric Fans	4	55	110	18-22	6	750
Televisions	2	70	70	5-10	4	150
Lightbulb	8	70	280	10-20	5	1400
Dishwashers	1	80	120	12-20	1	270
Air Conditioners	5	130	130		7	1400
Total			**1430**			**9720**

Based on the results of an earlier study by, the current analysis is based on the MLE275HD2 PV module, which includes 124 monocrystalline panels cells. [48]. Every module has a maximum voltage of 32.5V and a maximum current of 8.55A, and it can produce 285WP at conventional temperature settings (STC) of 1500Wm-2, 25oC, and 1.5 connected air volume. All it takes to achieve a peak power of 2565.8WP is to connect around ten units together via circuit connectors. Certain assumptions are made in this design, including that the number of cloudy days (NCC), the number of daylight hours in a year, the inverter and battery efficiency, and the optimal depth of discharge (DOD) will be, in that order, 0.8, 2473 hours, 0.85, 0.9, and 0.95. Table 3 provides specific precise information for every MLE275HD2 PV module. A 24V

DC bus signal voltage is employed, and about 440Ah of battery capacity is required, in order to minimize system distortions. This off-grid energy storage solution requires five 24V, 100Ah batteries at minimum. To control the PV array's short circuit, a 24/120A charge controller is also selected. To serve household appliances, the inverter system is designed with a 2.5kW inverter capacity, which is 20% greater than the total power of people using it. In Fig. 4, the off-grid solar panels system is displayed. Expanding upon the experimental work conducted by [49], as shown in Fig. 2, the monthly solar radiation becomes crucial in determining the PV system's capacity for power generation. An examination of the off-grid PV system's monthly energy production is provided in Fig. 5. August has the lowest potential, probably because of cloud cover in the spring, but months with high solar radiation, like February (519.82 kWh) and March (497.41 kWh), have the highest potential for energy production. Around 5488 kWh of electricity are expected to be produced yearly by the solar PV system, which will adequately support the 3142 kWh of electricity used by residential buildings. Any excess electricity could be supplied into the power grid, subject to modifications in PV technical characteristics, most notably the substitution of a grid inverter system with an off-grid inverter system. These findings highlight the necessity of installing a small-scale off-grid photovoltaic system in order to provide electricity for residential use.

Table 2 The PV module's specifications [13]

Specification	Rating	Unit
Highest power assessment (Pmax)	285	W
Quantity of cells	124	Pcs
Highest voltage of electricity (Vmp)	35.5	V
Highest power flow (Imp)	8.55	A
Performance of modules	20	%
Current short circuit voltage (ISC)	9.30	A
Voltage in an open circuit (VOC)	39.5	V

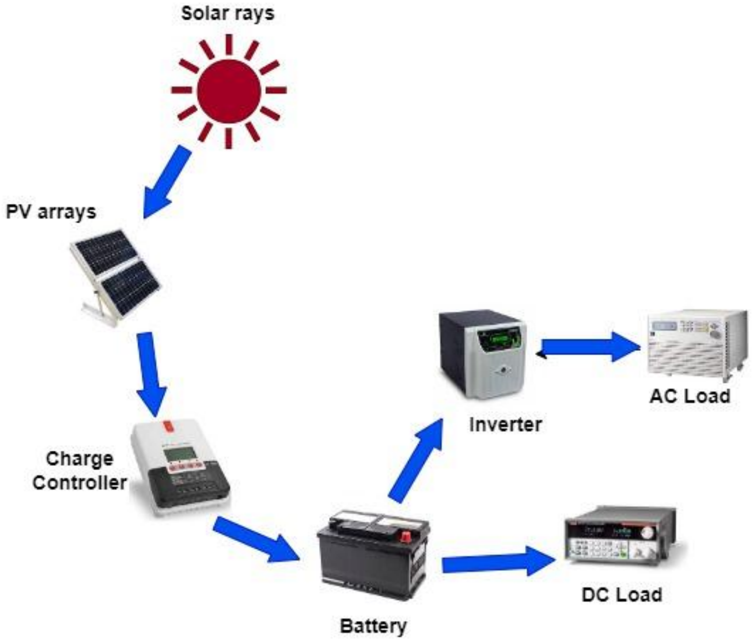

Fig.4 An off-grid photovoltaic system layout [48]

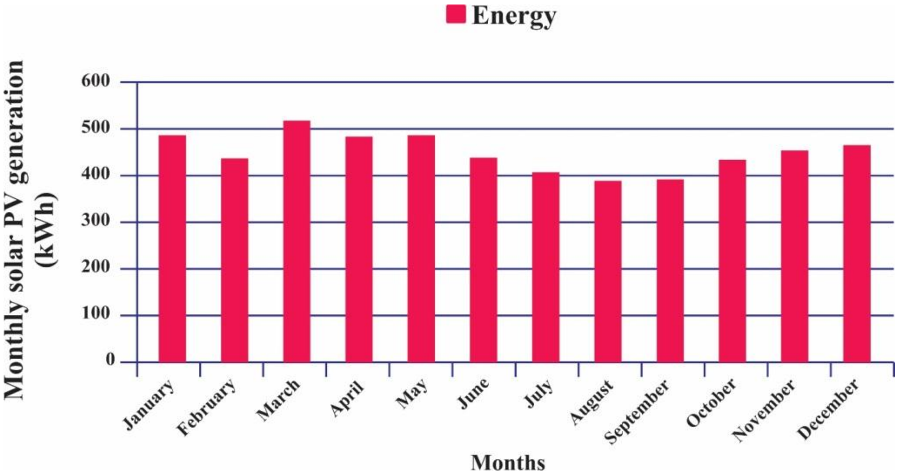

Fig.5 Monthly power output from an off-grid photovoltaic system [37]

The success of this study critically depends on the evaluation of the PV system's commercial feasibility. Its feasibility is determined by carefully examining a number of economic aspects. Using mathematical modeling, the following expenses are determined: US$5979.60, US$1568.00, US$796.00, US$424.80, US$497.96, and US$250.00 for the PV modules, inverter framework, battery mechanism, charge controller, setting up and upkeep and operation, in that order. The battery's PW for five, ten, and fifteen years is calculated to be US$987.12, US$953.00, and US$845.06, respectively. Amounts spent on maintenance total US$2466.74 in present well-worth (PW). The PW numbers take into account an inflation rate of 8.1% and a devaluation rate of 10%. Subsequent calculations yield the following results: US$13,110.85 for Life Cycle Cost (LCC), US$793.75 for Life Cycle Cost on an Annual Basis (ALCC), and US$0.28/kWh for Cost of Energy (COE). With electricity unit costs varying from ₦ 26.93 (US$0.207) to ₦ 43.9 (US$0.337), depending on the kind of residential building, the Abuja utility business currently has monopoly control over the distribution and marketing of electrical energy in the region. An evaluation of our COE in relation to local electricity rates highlights the study's financial sustainability. Comparing our research results to those of other studies, such as those conducted by [6] and [1], [2], [40], [50], which reported COEs of [TRY] 0.43/kWh and PKR 14.8 kWh-1, respectively, demonstrates the effectiveness of the numerical modeling tool in evaluating the techno-economic features of PV systems for off-grid power applications. Interestingly, our off-grid PV system's COE is lower than the modern grid's, illustrating that this model can be used to analyze the economic feasibility of rural communities across the globe, both developed and developing. This result is consistent with the analysis of grid-tied PV system feasibility [21] using the HOMER software, where the COE was US$0.103/kWh. In addition, our analysis shows a steady price for electricity, in contrast to [51] where the COE was US$0.60. Installing off-grid photovoltaic systems for home power generation is essential, especially in newly developed regional settlements where the existing infrastructure is inadequate. This strategy, as opposed to the current power network, not only lessens carbon impact but also promotes regional development. In areas where grid energy is unavailable, encouraging off-grid photovoltaic systems could control the migration of people from rural to urban areas, contribute to the reduction of poverty, and enable rural residents to run small businesses. This emphasizes how important it is to support economic initiatives like schemes that provide subsidies for renewable energy.

Table 3 Analyzing off-grid photovoltaic system costs.

Parameter	Cost per unit	Value	Financial expense ($)
Cost of PV modules	$1.95/$W_P$	2666.8Wp	5979.80
Cost of batteries	$4.2/Ah	24V, 440 Ah	1568.65
Battery's current value, n = 5			987.55
Battery's current value, n = 10			953.09
Battery's current value, n = 15			845.60
At 10% of the max output of the PV, the inverter	$1.31/$W_P$	2.5kW	975.50
Controller of charges	$6.5/A	122 A	424.40
Cost of installation	12% PV cost		568.20
Cost of operations and maintenance	4% PV cost		250.10
Current value of maintenance expenses			2466.00
Leveled expenses			13110.50
Annualized life cycle cost			793.65
Electricity costs			0.28/KWh

4. Conclusion

One of the first attempts to determine whether installing a photovoltaic (PV) system in Abuja, Nigeria, for off-grid power applications is techno-economically feasible is represented by this study. The obstacles presented by an expanding populace and problems in the electricity industry have outpaced government programs meant to supply dependable, reasonably priced, and easily available electricity. Using solar energy comes up as a key way to improve Nigeria's energy security while dealing with these issues. This is especially important considering that the average sun radiation is eight hours, and the daily global horizontal irradiance ranges from 2.5 to 9.5 kWh/m². Putting in place an off-grid photovoltaic system is a thorough way to utilize solar power. This paper's main objective is to use mathematical modeling to create an off-grid photovoltaic system for Abuja, Nigeria, that will produce energy for residential buildings. Among the technical aspects being evaluated are PV peak power, battery capacity, charge controller, inverter size, and sunlight exposure particular to a certain area. In terms of technology, it is possible to meet the 7.55 kWh daily electricity consumption of a residential home by utilizing certain values for the PV area, PV peak power, battery capacity, charge controller capacity, and inverter system size. These values are 16.56 m², 2666.80 WP, 24 V, 440.00 Ah, 120 A, and 2500 W, respectively. Life cycle cost (LCC), annualized life cycle costs (ALCC), and the unit cost of electrical energy are examined from an economic perspective. These economic factors have computed values of US$13,110.85, US$793.73, and US$0.18/kWh, in that order. The study shows the economic viability of establishing an off-grid PV system by comparing the PV system's unit cost (US$0.28/kWh) with the electricity distribution company's unit cost (US$0.207- US$0.337) in the case study location. This comparison takes into account the technology's capacity to reduce climate change and improve the electrical energy consumption of houses and condos. Even though the potential impacts of a PV system are not evaluated in this research, the techno-economic analysis's findings offer important new information about how much of an impact a PV system can have on lowering CO2 emissions because it generates electricity using solar energy rather than fossil fuels. The study recommends more research be done on the technology's effects on the environment and policy. In summary, it confirms that the unit electricity cost is legitimate and appropriate for assisting residential households in meeting their electricity needs. The study also proves that it is technically and financially possible to power Northern Nigerian residential buildings without electricity with an off-grid photovoltaic system. Therefore, it suggests that government agencies and other interested parties work together to further the growth and spread of solar PV adoption in Nigeria by putting renewable energy regulations into place.

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