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BRIDGING THE ENERGY DEFICIENCY GAP IN URBAN AREAS IN NIGERIA USING ROOF TOP SOLAR SYSTEMS

Dissertation under the Master of Science Degree in Energy for Sustainability supervised by Professor Pedro Manuel Soares Moura and presented to the Department of Mechanical Engineering, Faculty of Science and Technology, University of Coimbra.

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Abstract

The availability of an uninterrupted electricity supply has been a major challenge in Nigeria. As a result, a significant percentage of the population is forced to use alternate ways of providing an electricity supply to compensate for the frequent outages. Globally, solar panel costs have been reduced dramatically, due to improvements in technology that helped reduce the cost of production. Many urban homes in developing countries are now starting to adopt the on-grid systems which are used as a complement for when the grid is unreliable. The main objective of this dissertation is the assessment of rooftop solar PV in residential buildings in the Lagos Metropolitan Area Nigeria. To achieve this objective, this thesis utilized the survey of 50 residential buildings in the Alimosho local government area (LGA) in Lagos State, Nigeria to obtain electric load data. The developed study ensured the optimal design, performance analysis, and evaluation of the (LCOE) for stand-alone PV systems for the flat apartment and duplex building types in the study location, using Hybrid Optimization of Multiple Energy Resources (HOMER) software. The results of the optimally designed PV systems include a PV array (4.03 kW, 32.7 kW), lead-acid battery (17 kWh, 132 kWh) and converter (1.41 kW, 9.56 kW) for the apartment and duplex building respectively. The results of the analysis comparing the optimal design of the PV system with lead-acid battery and the PV system with a li-on battery of the flat-apartment building shows the LCOE value is respectively, 0.274$/kWh and 0.279$/kWh indicating that li-on battery is preferable due to its higher cost- effectiveness . The PV system design for the duplex building was compared with the option of using a stand-alone generator used to supply the load. The values of LCOE are 0.35$/kWh and 1.30$/kWh respectively. This clearly indicates that rooftop solar PV systems is better suited and can be used to bridge the energy gap in urban areas in Nigeria, as well as can be pivotal to attaining Nigeria's commitment to Sustainable Development Goal 7.

Keywords:

Solar Photovoltaics, Renewable Energy, Urban homes, HOMER, Nigeria .

Resumo

A disponibilidade de fornecimento ininterrupto de eletricidade tem sido um grande desafio na Nigéria. Como resultado, uma percentagem significativa da população é forçada a utilizar formas alternativas de fornecimento de eletricidade para compensar as frequentes interrupções. Assim, o objetivo principal desta dissertação é uma avaliação detalhada para a utilização de energia solar fotovoltaica em edifícios residenciais na Área Metropolitana de Lagos, Nigéria. Globalmente, os custos dos paineis solares fotovoltaicos têm vindo a reduzir drasticamente, devido a melhorias na tecnologia que ajudaram a reduzir o custo de produção. Em consequência, muitas residências urbanas em países em desenvolvimento estão a começar a adotar sistemas fotovoltaicos, que são usados como um complemento para quando a rede não apresenta fiábiliade adequada. Para atingir este objetivo, esta tese utilizou informação de 50 edifícios residenciais na área do governo local de Alimosho (LGA), no estado de Lagos, Nigéria. Foi feito o dimensionamento, assim como uma análise de desempenho e a avaliação do custo nivelado da energia dos sistemas fotovoltaicos autónomos para apartamentos e edifícios duplex, no local de estudo usando o software Hybrid Optimization of Multiple Energy Resources (HOMER). Os sistemas fotovoltaicos projetados utilizam paineis fotovoltaicos (4,03 kW, 32,7 kW), bateria de ácido-chumbo (17 kWh, 132 kWh) e inversor (1,41 kW, 9,56 kW), respectivamente para o apartamento e duplex. Foi feita uma análse para o sistema fotovoltaico com bateria de ácido- chumbo e para o sistema fotovoltaico com bateria de iões de lítio, apresentando um custo nivelado de energia de 0,274 $/kWh e 0,279 $/kWh, respetivamente. O projeto do sistema fotovoltaico para o edifício duplex foi comparado com o de um gerador autónomo usado para fornecer a carga. Os valores de custo nivelado de energia são 0,35 $/kWh e 1,30 $/kWh, respectivamente. Isso indica claramente que os sistemas fotovoltaicos solares podem ser usados para suprir a lacuna de energia em áreas urbanas na Nigéria, bem como podem ser fundamentais para atingir o compromisso da Nigéria com o Objetivo de Desenvolvimento Sustentável 7.

Palavras-Chave

Solar Fotovoltaico, Energia Renovável, Edificios Urbanos, HOMER, Nigeria.

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List of Acronyms

GDP Gross Domestic Product

GWp Gigawatt peak

LCOE Levelized Cost of Electricity

LGA Local Government Area
MW Megawatt

NPC Net Present cost

PV Photovoltaic

SOC state of charge

WTP Willingness to Pay

1. Introduction

1.1 Motivation

Energy is the backbone of the progress of any nation. With an efficient energy supply, economies can also experience steady growth and bolster security. In recent times, countries in the developing world have been registering high population growth rates and an increasingly high living cost. As a result, this has worsened the state of the energy supply. However, without a reliable energy supply, these countries face many problems starting from the lack of piped water, poor sanitation, and communication issues. Countries ravaged by these problems are looking into renewable sources of energy, such as rooftop solar systems, which will not negatively affect the environment, as the main solution for the short and medium-term (Lee et al., 2018).

In Nigeria, there is an ongoing failure to supply adequate power to both residential and industrial sectors. regardless of the growing economy and the country's status as Africa's largest oil producer. Currently, there is potential to ensure 12,522 MW of electric power with the existing power plants. However, only about 4,000 MW are in operation, which is insufficient. The grid power is unreliable and unable to meet growing demand, resulting in frequent load-shedding and outages, also has supplied limited access to clean and modern energy services to most Nigerians'. Additionally, the terrible state of the country's electricity supply has resulted in a widespread self-generation of electricity from alternative sources in Nigeria since more people are forced to rely heavily on generators. This caused the use of petroleum products to increase by 75% as of 2012 (Udoudoh and Umoren, 2015).

Nigeria has been ravaged by the energy crisis for more than 3 decades. This has led to the collapse of industries and commercial activities declining at massive rates. The situation has been aggravated further by the country depending entirely on petroleum as a source of energy (Akorede et al., 2017). Nigeria's energy reserves are unparallel to none in Africa's continent. The country is the leading source of oil and gas reserves, followed by Algeria. There are also other energy sources, but their availability and use rely on government policies. The government's role is critical in getting the country from dark ages' energy sources such as firewood, which adversely affects the environment (Emodi & Boo, 2015).

The rooftop solar systems refer to panels that can harness energy through the solar cells and convert the energy into electricity. The adoption of rooftop solar systems will help reduce the problem of energy in developing countries and improve the quality of life. Most urban areas in Nigeria use generators with fossil fuels in their daily activities, which adversely affects the environment. However, to adopt a rooftop solar system, it is essential to set up requirements for the initiative. This dissertation aims to assess the benefits, as well as the constraints of rooftop solar systems in urban residential buildings.

1.2 Objectives

This dissertation aims to evaluate the driving factors and barriers to achieving sustainable and reliable electricity supply in urban residential buildings. To accomplish this aim, the following objectives will be attained:

- Assess the energy demand and renewable energy resources potentials of the selected areas.
- Assess the increase of reliability that can be achieved with the rooftop solar systems option (compared with just relying on the grid).
- Compare the rooftop solar systems with the actual backup options (diesel generator).

The above research objectives intend to answer the following research questions:

- How urban dwellers can increase access to electricity without complete reliance on the grid for their daily needs keeping in mind the weather constraints of such areas?
- What is the gradual impact of adopting stand-alone home solar systems in urban areas and the environment at large?

1.3 Thesis Structure

This thesis comprises six chapters. Chapter one (1) introduces the thesis topic and the challenges addressed by this work. Chapter two (2) identifies the recent developments and relevant studies relating to the research topic, namely addressing: Overview of Power Crisis in Nigeria, Rooftop PV Potential in Nigeria, Citizen Participation in Willingness to Pay (WTP), and Dust and PV Performance. Chapter three (3) explains the method(s) used for the development of this work, providing details about the activities integrated to attain the thesis objectives. Chapter four (4) introduces the data and the case study and Chapter five (5) presents the results and discusses them. Chapter six (6) is the closing chapter and discusses the main takeaway from the project, as well as introduces recommendations for further works.

2. Literature Review

In this section, a literature review of the research is presented. The review focused on the main components of the thesis, which include Overview of Power Crisis in Nigeria, Rooftop PV Potential in Nigeria, Citizen Participation in Willingness to Pay (WTP), and Dust and PV Performance.

2.1 Overview of Power Crisis in Nigeria

Most developing countries in the world face power shortage problems due to lack of access to the electrical grid, unstable or insufficient power supply characterized by outages and blackouts, and excessive costs of energy. These countries are challenged by the power generation methods and resources which leads to a lack of development and provision of basic social amenities such as healthcare and education. This work is focused on the use of alternative sources of energy, particularly solar energy to bridge the gap between the demand for energy and its supply in urban residential homes with a specific focus on Nigeria. In this literature review, the affiliated work, related to the topic will be examined to critically understand the root cause of the problem, as well as find any gaps that may exist in the research area. The literature will be presented in a thematic order, where an overview of the power shortage will be examined, as well as other academic documents suggesting the solutions to the problem. Recommendations will be made based on the identified gaps or clarity made in obscure areas.

Most people in Sub-Saharan Africa and South Asia live their daily lives without electricity according to a World Bank report released in April 2018 (World Bank, 2018). Although the number of people with access to electricity has been steadily increasing, there is still a high energy deficiency in this essential commodity, which impedes progress for a sizeable proportion of the world's population and negatively affects a wide range of development indicators including education, food security, health, livelihoods, and poverty reduction. The number of people gaining access to electric energy has been increasing since 2010 to around 118 million each year, as presented in **Error! Reference source not found.**, but this should be accelerated to meet Sustainable Development Goal 7, which is ensuring access to affordable, reliable, sustainable, and modern energy for all by 2030 (World Bank, 2018).

Universal access to energy is still a challenge in most urban areas in Nigeria, hence the need to complement the World Bank's Last Mile project to bridge the energy gap. There is a high shortage of power in Nigeria, with about 47% of the population having no access to electricity and those who have access facing regular power cuts. This accumulates a cost of $28 billion on the country's economy, an equivalent of 2% of its Gross Domestic Product (GDP) (World Bank, 2020). This deficit has crippled businesses that depend on electricity to function, especially in urban centers. Currently, power supply difficulties are experienced around 60% of the time in Nigeria (Aliyu, Ramli, Saleh, 2013).

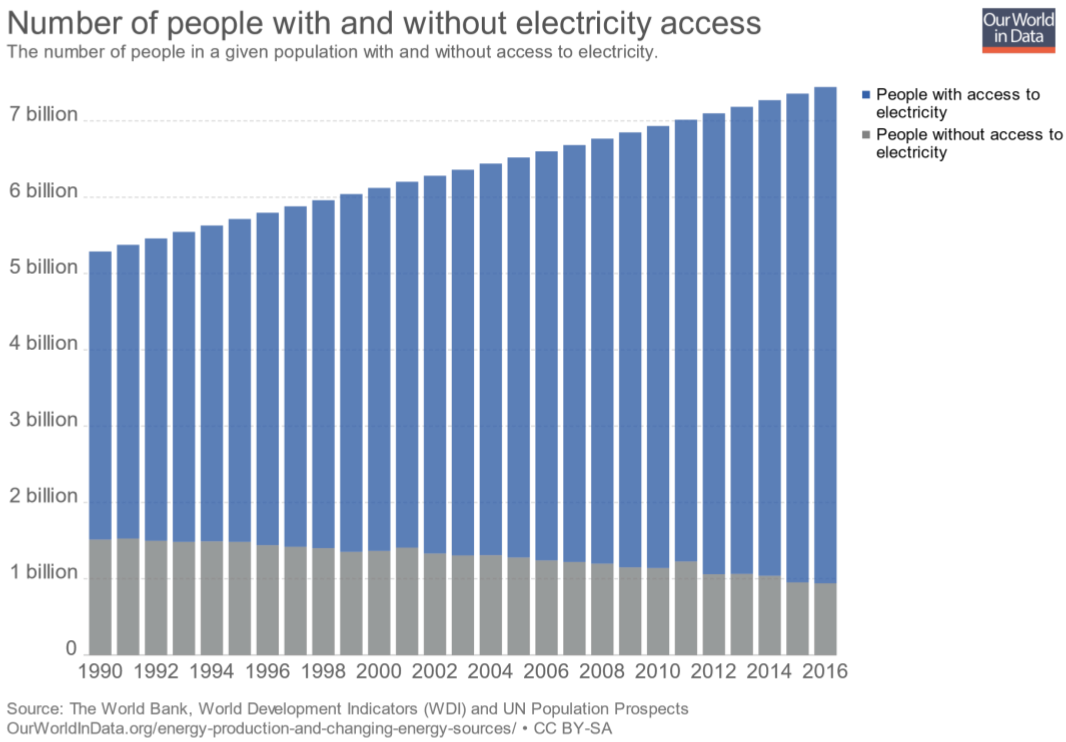

Figure 1: Number of people with and without electricity access (World Bank, 2018)

The country experiences at best only four hours of daily power supply with other days going without power at all. The Nigerian government controls the transmission assets of the power supply with little effort made to mitigate the situation in a bid to attract foreign investors (Ogunleye, 2017). The power problem is the major obstacle in the development of the country with the situation receiving both national and international attention. This has prompted many researchers to focus on ways of solving the energy problem in the country while considering the limitations imposed on alternative sources of energy such as oil and coal. Research has moreover focused on the available opportunities and challenges based on the country's topography with its mountainous and riverine regions (Okedu, 2015). This is considering the growing concerns on the dangers posed by the increasing use of fossil fuels prompting the world to shift to cleaner sources of energy (Ezugwu, 2015).

The sources of energy in Nigeria include coal which accounts for 0.4% of the energy, oil which accounts for 24.8%, natural gas 39.8%, and hydroelectric power which makes up 35.6% of the country's energy sources. Although Nigeria has a large natural supply of coal and would be the cheapest resource to develop into energy plants (Gujba, Mulugetta & Azapagic, 2011), the black carbon emissions have detrimental effects on the environment due to their light-absorbing qualities. In reviewing the effects of coal as a source of energy for developing countries, (Novakov light-absorbing 2013) states that when black carbon lands on snow and ice, the reflective properties of ice are decreased, and more melting occurs. Moreover, the current policy discourages carbon emissions in Nigeria coupled with the movement towards cleaner energy (Matthew et al, 2018).

Although Nigeria is the seventh-largest supplier of oil in the World which makes it readily available as a source of energy (Ejiogu, 2013), its environmental impact including oil spills, cost of refinement and pipeline sabotage by residents leads to air, water, and land pollution, coupled with the emissions that arise from the combustion of the oil (US Energy Administration, 2013). Additionally, there are barriers related to the country's lack of control over its oil production areas hence lack of access. Natural gas accounts for the largest percentage of energy production in the country. Although it has lower greenhouse gas emissions than coal and oil, the unconventional means of its mining leads to substantial amounts of methane leaks into the atmosphere (Hultman, et al., 2011).

The Hydroelectric power production in the country is limited due to restrictions on dam construction on Nigerian rivers that cause stagnation and change of river profiles. Although it is environmentally friendly and uses renewable resources associated with less greenhouse emission after development, it also disrupts water levels of the river and reservoirs that form behind the barriers cause flooding and displacement of the area (Aliyu, Ramli & Saleh, 2013). The country has no potential for further development for hydroelectric power because of the dependence on the seasons for water supply (Ajayi, 2009). Nigeria has been in an energy crisis for over a decade despite numerous efforts to supply a solution. Most of the literature making different proposals in this sector are based on nuclear power, since Nigeria has easy access to uranium plants (Ejiogu, 2013), wind energy although it is a limited solution, and hydroelectric power which has no further potential for development. Areas that have a high potential for wind production and installation of wind turbines are in the northern parts of the country which have the least development of power grid. The nuclear energy proposal on the other hand is a satisfactory solution since it would give an output of around 10% of the county's power supply; twice the recommended amount (Global Energy Network Institute, 2014). However, nuclear energy production requires a stable energy grid to be supported and an independent off-site power is needed for its sustainability, which Nigeria does not have. Moreover, the proposed sites are in unstable areas where the Nigerian government does not have control over the workings of the local militant groups. This, therefore, leads to the need for an alternative power source, hence the rooftop solar systems.

2.2 Rooftop PV Potential in Nigeria

The use of solar power to solve the energy crisis in developing countries has had a lot of attention due to its economic viability and potential (Arnold, 2010), especially in Africa. Several pieces of research have been done to figure out the possibility of decarbonizing the Nigerian electricity sector and ensuring a stable power supply using rooftop solar PV. The most relevant and closest to this research is done by Michael Dioha and Atul Kumar on rooftop solar PV for urban residential buildings in Nigeria. The study finds the gap between power generation and consumption capacity that creates a large deficiency, while most of the population has no connection to the national grid (Dioha & Kumar, 2018). Using a computationally logical methodology to estimate the technical potential of rooftop solar PV in urban residential buildings in Nigeria, as well as the PVSyst software to estimate the annual yield of rooftop PV in selected cities across the country, the paper estimates that Nigeria has a 796 km^2 potential of solar power for rooftop PV and grid installation producing an estimate 124 GWp annually. as presented in Figure 2.

From their findings, a typical urban residential building has a gross roof area of 140 m^2, out of which only 68 m^2 is suitable for PV installation after deducting clearance, shading, and other domestic miscellaneous. This accounts for about 49% of the roof area available for PV installation. The paper also estimates the technical potential for residential urban buildings in Nigeria to be 124 GWP, which is about ten times the current electricity generation in the country (GENI, 2017). The study found that Nigeria has a relatively huge potential for solar PV in urban buildings which would be a suitable substitute for fossil fuel power and thus bridge the power deficiency gap in the country.

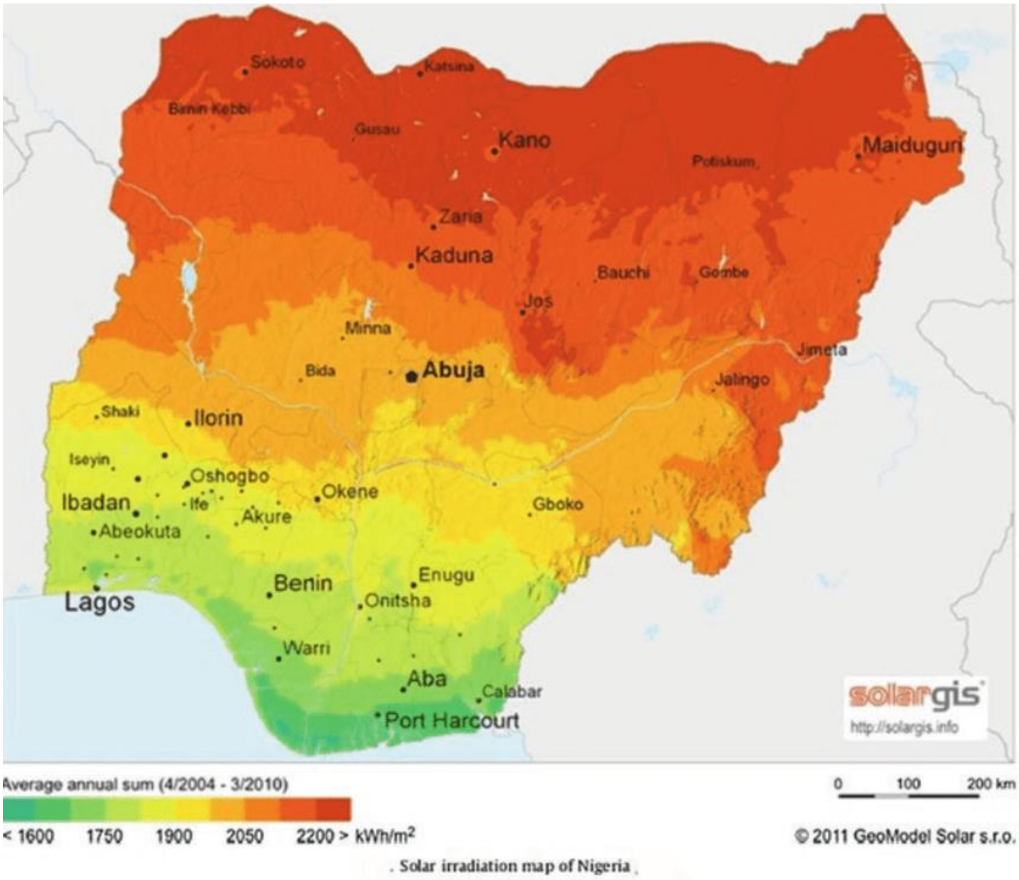

Figure 2: Solar energy potential of Nigeria showing sun irradiation (Solargis.info, 2011)

Although the paper attempts to estimate the technical potential of rooftop solar PV in urban residential buildings in Nigeria, the market and economic potential will reduce these estimates in practical terms. The research also found that rooftop solar energy will be higher than the average tariffs in Nigeria hence not yet financially attractive for the R1 (Residential in rural areas with consumption below 50 kWh units), R2S (Residential non-rural - Non-Maximum Demand - consumption above 50 kWh), and R2T (Residential non-rural - Non-Maximum Demand) categories of households in Nigeria. Suggestions are made for the government to provide subsidies to accelerate the installations in their initial stages as has been seen in other countries like Italy, China, and Japan (Shahsavari & Akbari, 2018).

The review by (Appelbaum, 2019) puts more focus on the shading and masking affect the performance of photovoltaic systems compliments the study on the solar PV potential in which it was found to contribute to a lower rooftop area for the installation of the solar PV in Nigeria. The study identifies two effects related to the deployment of photovoltaic collectors in subsequent rows: shading and masking both of which reduce the incident solar radiation and hence reduce the electricity generated by the PV field. These effects lead to a potential power loss of between 2.8% and 25% due to these effects (Appelbaum, 2019), hence should be put into consideration in the installation of rooftop solar PV.

2.3 Citizen Participation in Willingness to Pay (WTP)

Any project aimed at solving a social or economic problem relies heavily on citizen participation and involvement (Mxhosa, 2017). Therefore, citizen participation is crucial in transforming global electricity infrastructure. In their research on assessing the urban household's willingness to pay for standalone solar photovoltaic systems, (Ugulu & Aigbavboa, 2019) state that household involvement is particularly vital for nations with underdeveloped grids and widespread electricity outages like Nigeria. There is a high willingness to pay from high-income earners according to a study conducted in Cape Peninsula, South Africa (Oliver et al, 2011). Another study on the willingness to pay based on household income was conducted on Greek households, where Sardianou and Genoudi reported that the middle-aged, highly educated people displayed greater willingness to pay for renewable alternative sources of energy (Sardianou & Genoudi, 2013) as was the case in Shanghai, China (Hast et al, 2015).

Ugulu and Aigbayboa concluded in their research that there is a remarkably high willingness to pay for solar PV in Nigeria compared to households in Asia and Africa. The WTP was further increased in the prospect of government incentives, where consumers were recorded to be more willing to pay for the solar PV. The WTP was increased by 87% due to the prospect of government incentives (Ugulu & Aigbavboa, 2019). The other factor to consider in the installation of rooftop solar PV is home ownership concerning WTP. The research showed no correlation between WTP and home ownership in Nigeria, as is also the case in Europe (Leenheer et al, 2011), unlike in rural Kenya where home ownership was a significant factor for households' WTP for PV (Abdullah & Jeanty, 2011). Therefore, from this research, it is safe to conclude that Nigerians will be willing to pay for rooftop solar PV and collaborate in bridging the energy deficiency in the country.

2.4 Dust and PV Performance

The installation of the rooftop photovoltaic (PV) devices should take into consideration their performance. Accumulation of dust has an adverse impact on the PV devices by degrading their performance (Chanchangi et al, 2020). This is due to the exposure of the PV panels to absorb maximum solar energy. Dust accumulation has been known to be the biggest challenge in the solar PV panels across the world, and for Sub-Saharan regions, the effect is greater given the higher presence of dust particles in the atmosphere. These dust particles not only cover the surface of the solar panels but also reduce the solar intensity in the regions hence reducing the peak generation periods for energy. In their research on dust and PV performance in Nigeria, Chanchangi et al stated that there is energy loss from PV due to dust and therefore made a performance review on the measures to mitigate the dust issue. The authors note that there is a need for research of the geopolitical regions in Nigeria to get data that can be used for designing PV module systems.

Dust is generated from volcanic eruptions, desert storms, industrial emissions, construction debris, highway activities pollen, plant material, vehicle emissions, microscopic organisms among other sources (Darwish et al, 2015). As presented in **Error! Reference source not found.**, The paper discusses the effects of excessive dust from Saharan dust that causes a severe impact on PV performance in the country during the Harmattan period. This is because the country is adjacent to the Sahara Desert and most sandstorms originating from the Sahara region are deposited on the roofs of most urban areas in Nigeria when the Harmattan wind reduces its speed as it travels through longer distances. This among other sources of dust attenuates solar radiation by scattering and absorption of the rays. These deposited dust on the PV surface get mixed with light rains and cause cementation due to the mixture of dust particles and light rains on the surface, which causes the most considerable PV performance degradation until the onset of heavy rains which washes the dust away (Chanchangi et al, 2020).

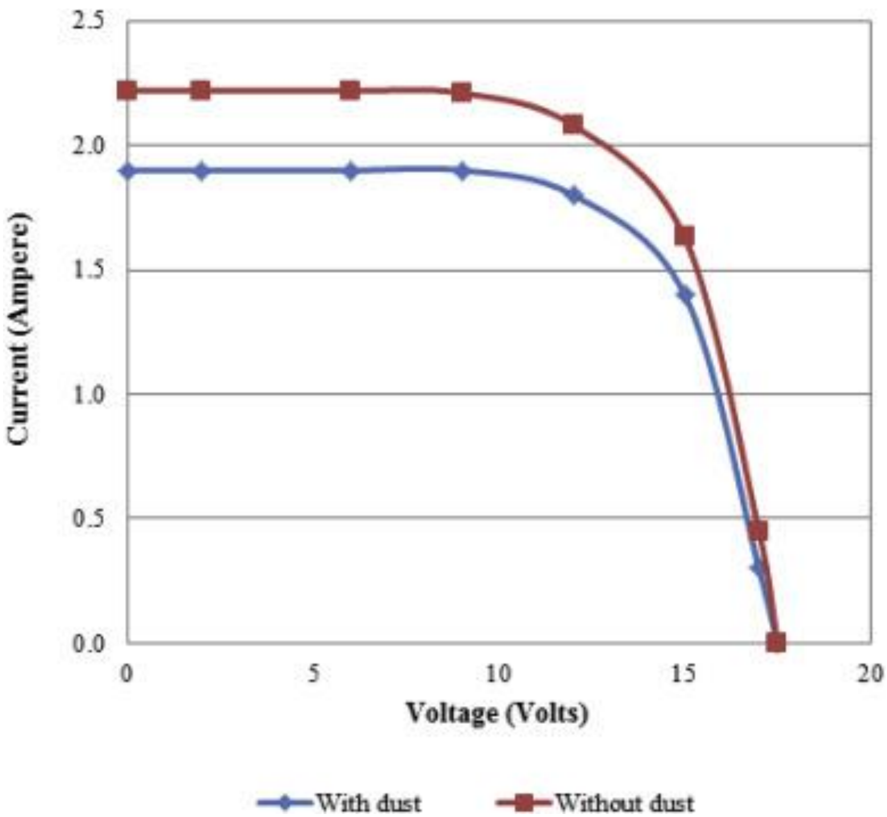

Figure 3: Photovoltaic module Current –Voltage (expressed in amp vs. volt) variations with dust for monthly panels' exposure (John K. Kaldellis, 2016)

Such a study (Chanchangi et al, 2020) goes ahead to supply dust mitigation techniques to restore the performance of the technology after dust accumulation. However, there exists no evidence of implementation of the suggested mitigation techniques, although it reinforces that the natural cleaning technique of rain, wind, and gravity will be active on the PV installations once exposed outside. The research findings accentuated those of an earlier study on the same effects of dust on PV panel performance was carried out by Sulaiman et al in 2011 where it was concluded that there is a reduction to peak power generate due to the accumulation of dust and mud up to 18% of the total power generation during the peak generation (Sulaiman et al, 2011). From these findings, considerable caution should be made in the installation of the PV systems in its bid to bridge energy deficiency in the country. For maximum operation, the government should consider any of the suggested dust mitigation regimes to reduce the dust from vehicles and construction sites as well as other artificial dust sources.

In conclusion, solar energy is the best alternative to solving the energy crisis in developing countries, with specific regard to Nigeria. From the review of the relevant literature linked to this topic, it is evident that installation of the PV systems will be well received by the residents of most urban centers with weak or lack of power and constant power cuts that cripple businesses and their daily lives. With Nigeria being the worst hit by the power crisis, Solar energy will generate more energy than its current capacity which can barely sustain half of its 170 million population. As found, energy is at the core of any industrialization and sustainable energy is at the cradle of improved living standards as well as the provision of basic social amenities (Brutschin & Fleig, 2016).

Therefore, solar power installation in the urban centers is a project whose time has come, and the government should foresee its implementation and incentivize it through the provision of capital incentives for installation. It is clear from the reviewed literature that most Nigerians will be willing to pay for the PV installation in their homes regardless of the home ownership. With government incentives, the reception of the project will be over 90%, which means that the government can capitalize on the economies of scale. The identified gaps in the reviewed literature include the absence of a clear and concise methodology of the installation of the solar systems and whether a larger outlook can be comprehended in which the cumulative power generated can be channeled to the national grid. Moreover, a workable plan should be adopted in which the two grid systems main grid and microgrids can exist in a symbiotic manner for energy sustainability in the country (Bhandari et al, 2014). The hybrid grid system should make up solar photovoltaic, wind, and hydro energy sources. **Error! Reference source not found.** presents the renewable energy potentials (solar PV, hydro, wind, and concentrated solar) of the various regions in sub-Saharan Africa.

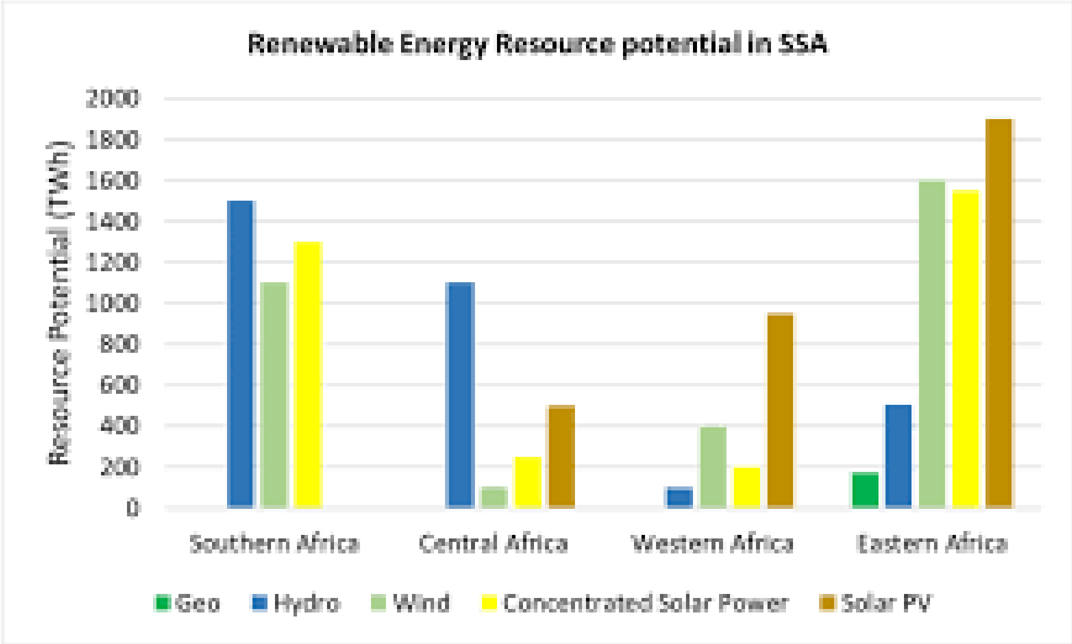

Figure 4: Distribution of renewable energy resource potential in SSA (Cartwright, 2015.)

3. Methodology

The specific approach employed for this work involves the following activities, firstly the representative location was selected based on the area's electricity access situation and the economic condition of the dwellers to pay for the services in different households. The relevant data of the energy demand for each household was then evaluated and solar energy resource potential for the selected location was analyzed. For the stand-alone PV system design required to meet the electrical load profile of the residential buildings at the selected location, the components like solar PV, battery, inverter, were modeled with the Homer Pro software (Homer Energy, 2021). Afterward, the feasibility of the modeled system was simulated with Homer Pro to get the optimum design of the solar PV system. The technical and economic assessments were conducted using HOMER Pro and the economic analysis was based on the Levelized Cost of Electricity (LCOE). The optimal design of the solar PV system was compared to a Diesel Generator of equivalent capacity through established criteria implemented using Homer Pro. Figure 5 depicts the research framework.

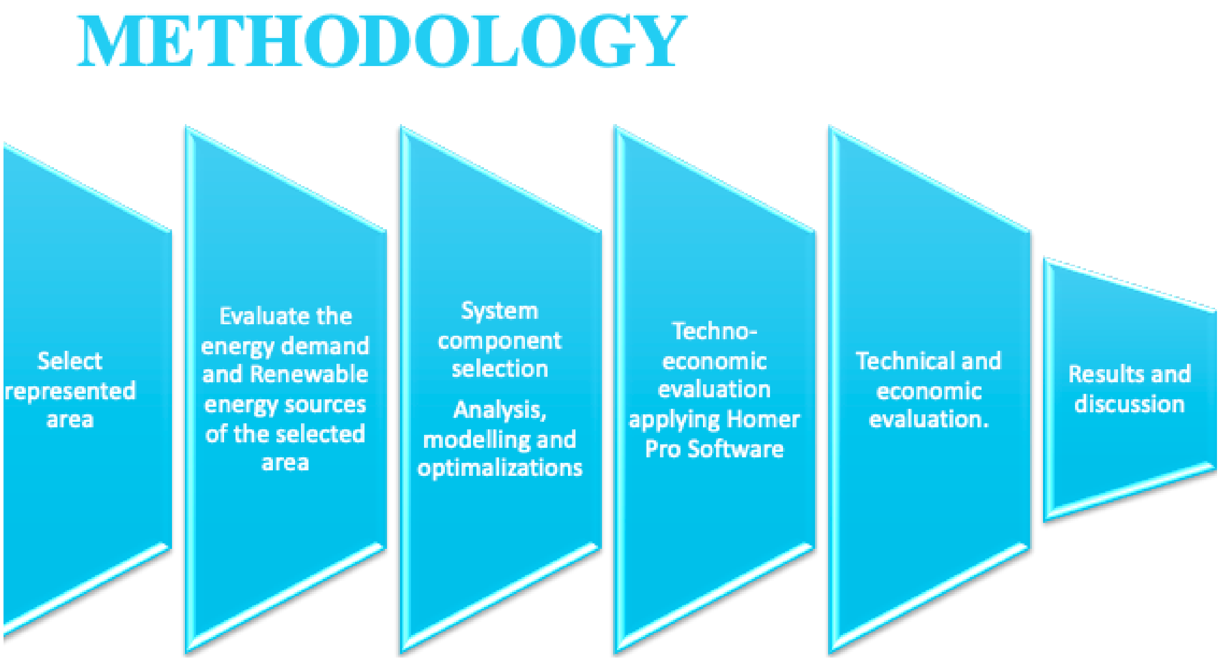

Figure 5: The Research Framework

3.1 Selection of Representative Area and Obtaining Data

The urban residential households selected for this work were based on technical feasibility criteria classified into three categories including geographical conditions, economic profit, and environmental benefits (J. Liu et al 2017). The criteria are shown in Figure 6, which directly affect the performance of the stand-alone system in the largest Local Government Area of Lagos state according to the official 2006 population Census (National Population commission Nigeria, 2010). The principal data obtained in the category of geographical conditions include solar radiation, elevation, and temperature. As for the criteria in economic profits and environmental benefits, the Levelized Cost of electricity method, which estimates the cost of lifetime-generated energy, was used as a benchmarking tool to assess the cost-effectiveness of different energy generation technologies (OECD, NEA/IEA, 2010). There are five different residential building types in Nigeria as presented by Jiboye (2014): duplex, single-family bungalow, a traditional courtyard, apartment, and face-me-I-face-you. For this study, the duplex and apartment building types were adopted considering that they are the most popular residential building type in Lagos.

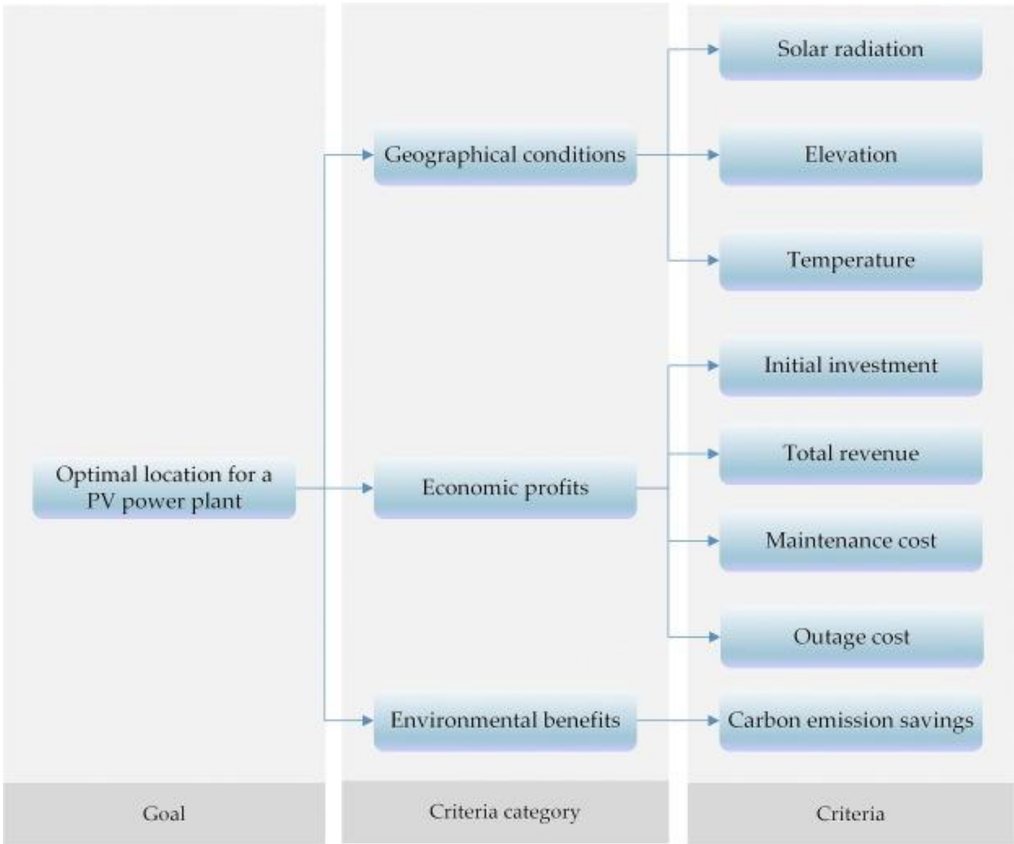

Figure 6: The decision-making criteria for PV power plant site selection (JichengLiu 2017)

3.2 Energy Demand and Renewable Energy Generation Potential

The daily energy demand was determined based on the number of households, the energy consumption of the appliances in each household, such as television, electric fans, refrigerator, and others. The assessment of load was done considering the load of a typical apartment residential building type in Alimosho LGA. The power rating and the typical period of operation were recorded. The load assessment was done by calculating the power rating of the usual appliance and the hours of operation.

However, for this study, available data of the minimum and maximum loads of apartments were used to apartments and duplex building types, respectively, across the selected location, were considered for this research because they are the most common in the urban household, as adopted from K.E. Enongene, et al (2021). The hourly energy load for each building was obtained by summing up the power rating of all the appliances used during the 24 h period of the day. The load profile was determined using Microsoft Excel to record the hourly electricity load profile. The daily load profile for each dwelling was obtained as an average of the load profile for the seven days of the week. K.E. Enongene, et al (2021). The data were fed into the software in the form of time data series (Bahramara et al. 2016). The load profile of apartment and duplex building type respectively was gathered during a comprehensive site survey conducted by K.E. Enongene, et al. The load profile of apartment building type is presented in Figure 7, and the load profile of duplex building type in Figure 8.

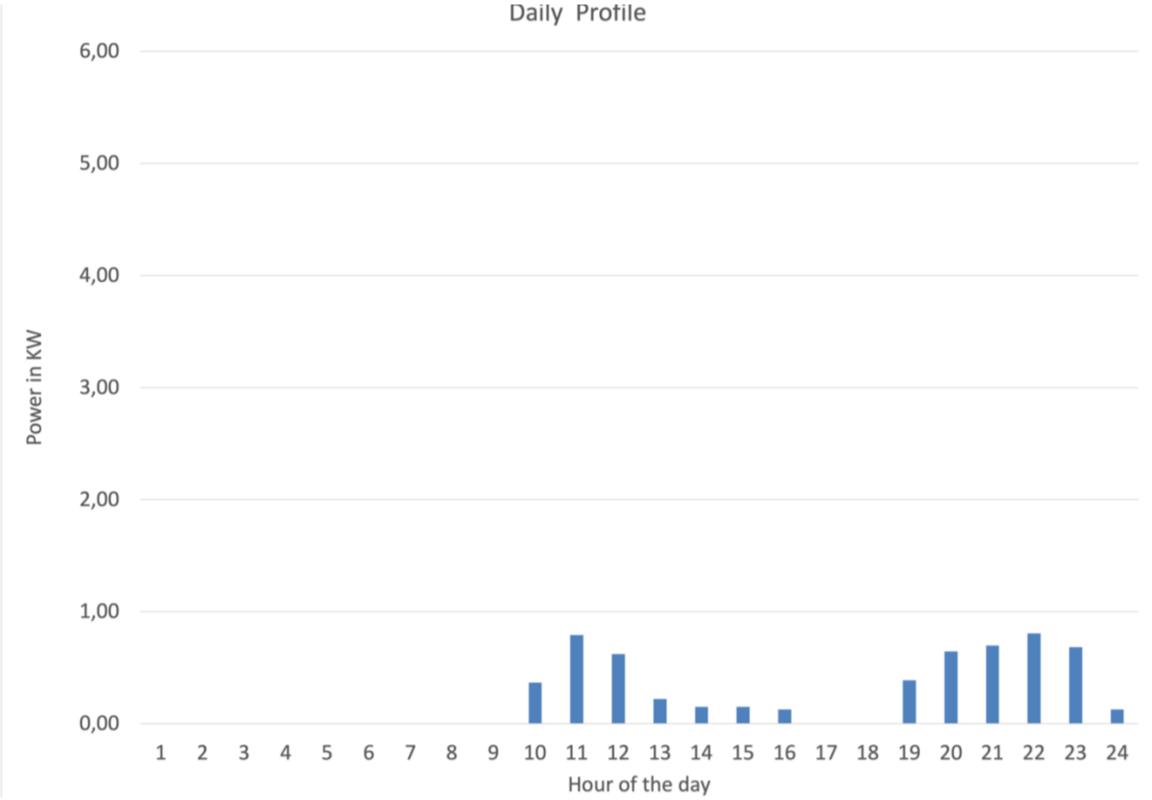

Figure 7: Minimum load of apartment building type across Alimosho LGA

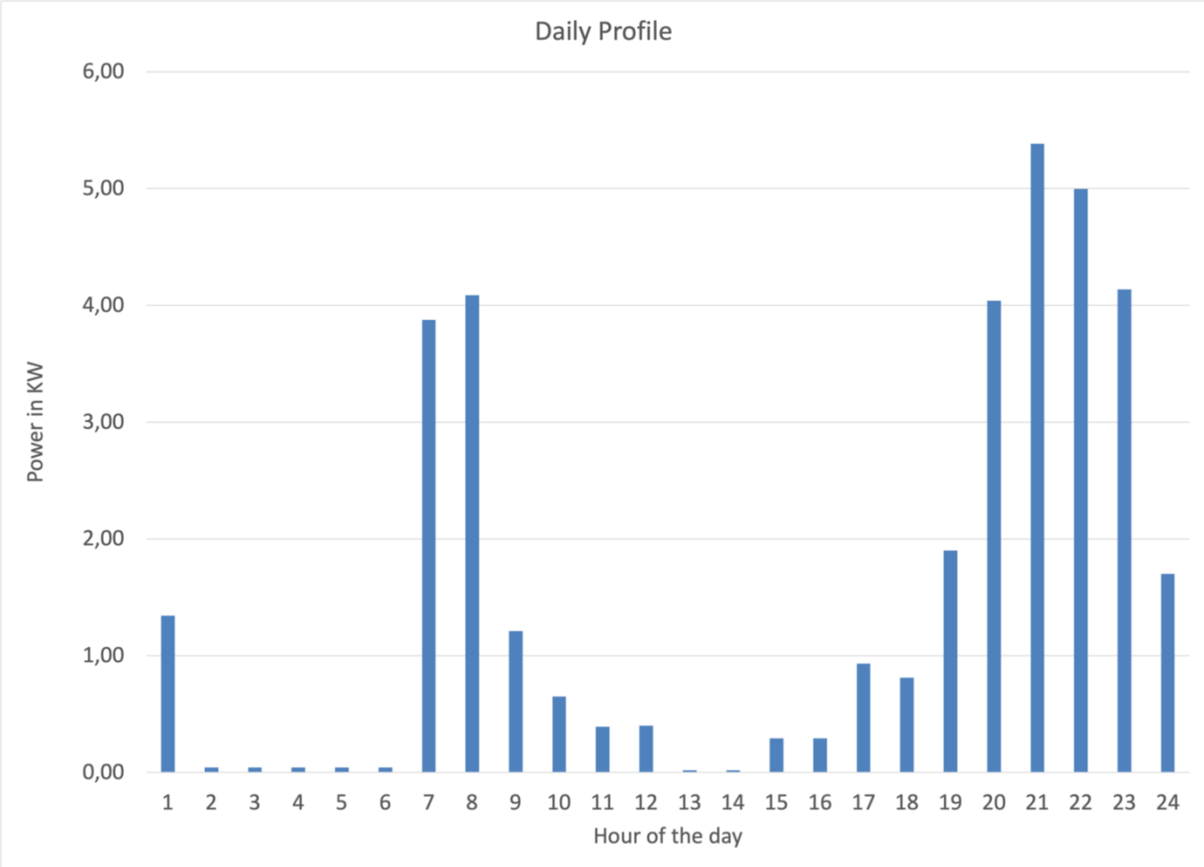

Figure 8: Maximum load of duplex building type across Alimosho LGA

The potential of solar energy at the selected location was analyzed based on mean monthly global solar radiation, as well as the monthly clearness index (Olatomiwa et al. 2016). Monthly solar radiation data from the National Renewable Energy Lab database for this specific location in Komak, Alimosho coordinated at 06°34′5″N 3°15′4″E were obtained. The average solar radiation was at 4.74 kWh/m2 /day. The monthly solar radiation and clearness index can be referred to in Figure 9.

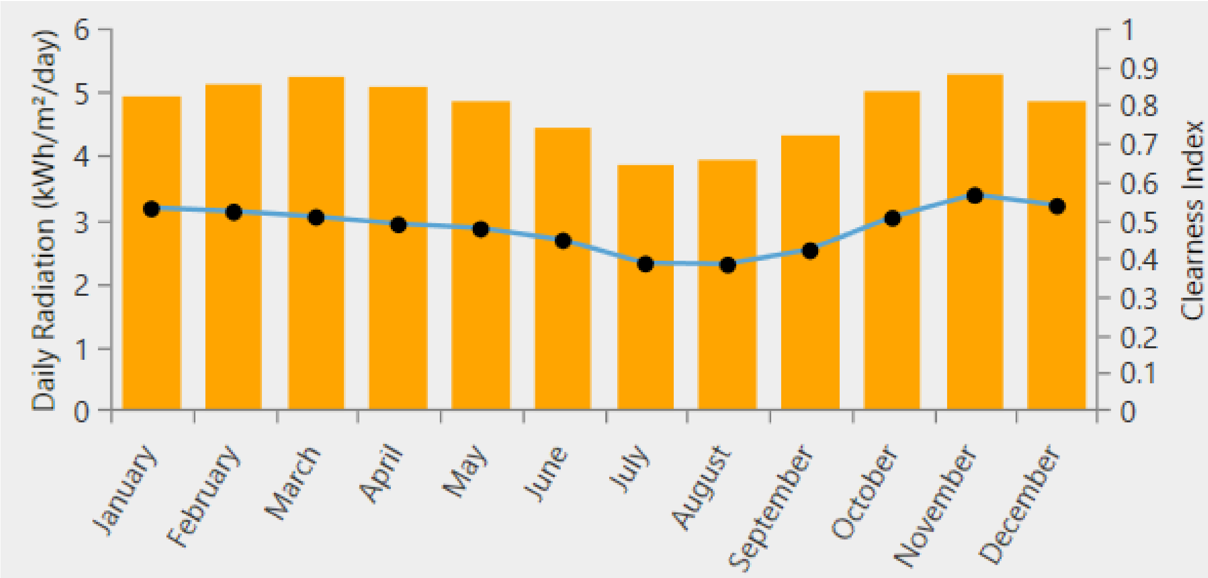

Figure 9: Monthly Average Solar Global Horizontal Irradiance of Alimosho LGA from Homer Pro

3.3 Modeling, Design, and Simulation of Rooftop Solar Systems.

A stand-alone solar PV system was designed for this study to meet the energy demand for the household. The simulation of feasibility study of the Solar PV design was implemented with the HOMER Pro software, using parameters like solar radiation, load profile, PV-system components (battery, PV-system array, and converter) technical and cost details, and the solar resource data (Global Horizontal Irradiation-GHI). Based on the lowest net present cost (NPC) with its corresponding cost of energy (COE), the optimal design is chosen. Figure 10 presents the schematic diagram of the completed stand-alone solar system which consists of PV array, converter, and batteries for the backup system.

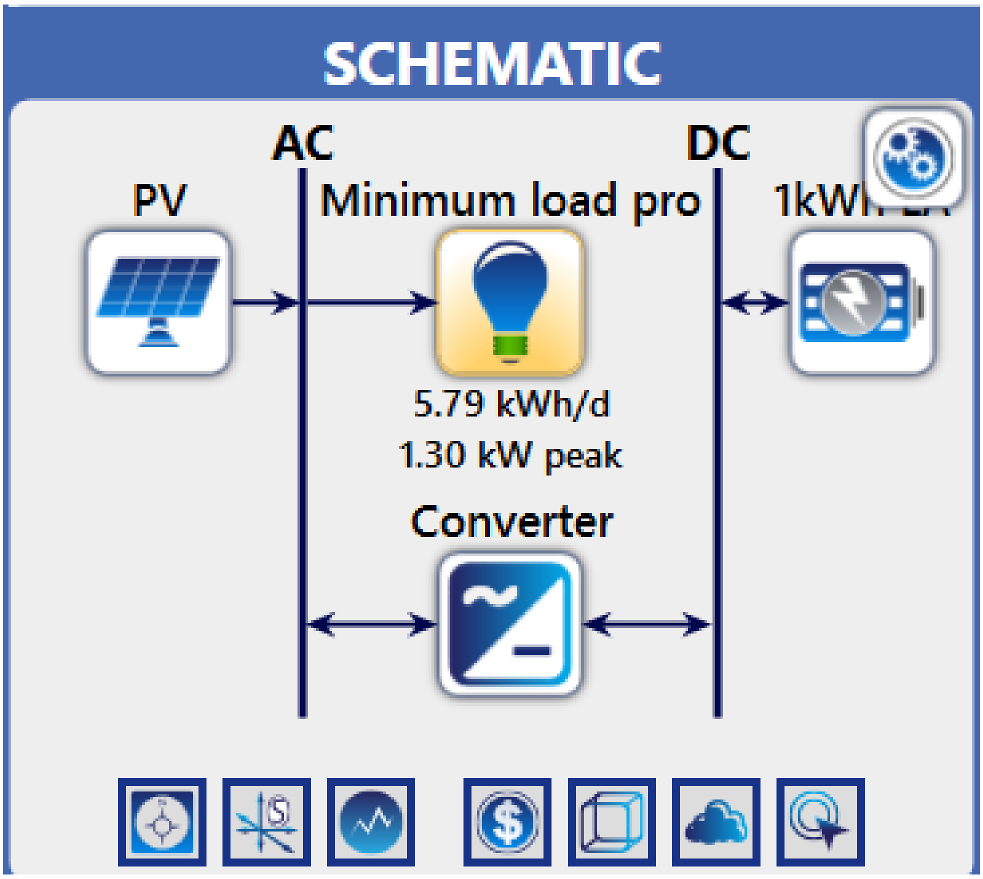

Figure 10: Schematic diagram of a stand-alone solar system

In the simulations, the best-designed solutions were compared with the backup solutions currently used (diesel generator with 15, 000 operating hours lifetime), using an equivalent solution with the same rated continuous output power as the stand-alone solar PV system. Figure 11 shows the schematic diagram of the Diesel Generator.

The technical and economic assessments were conducted using HOMER Pro and the economic analysis was based on the Levelized Cost of Electricity (LCOE). The main components which are used in both stand-alone PV systems and diesel generators were analyzed economically by inputting installation cost, replacement cost and operation & maintenances cost of all the components into the homer pro software.

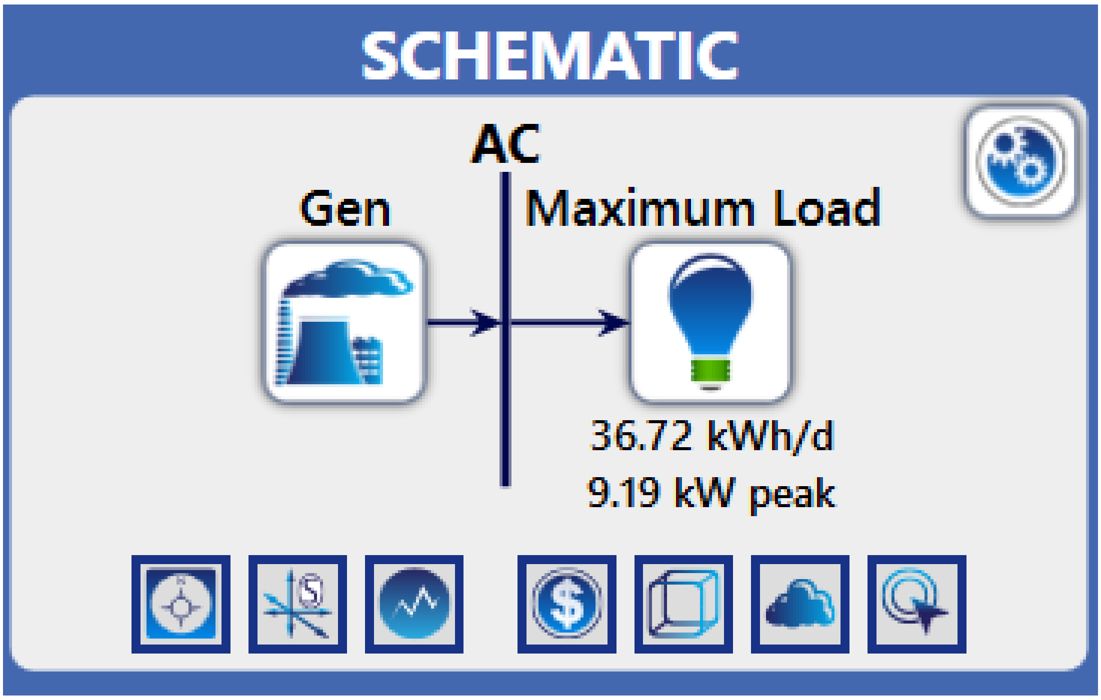

Figure 11: Schematic diagram of the diesel generator

4. Data and case study

4.1 Study area description

Alimosho Local Government Area was selected for the case study. For a long time in Alomosho LGA, most of the population has been depending on diesel generators to produce electricity due to the inadequate power supply from the grid. This situation is not acceptable as fossil fuels are harmful to the environment and are not cost-effective, as well Renewable energy source availability is enormous in this study area with the average solar radiation at 4.74 kWh/m^2 /day (I.J Mwakitalima, et al 2021). According to Homer, the solar daily radiation for this precise location Odo Eran, Ikotun, in Alomsho LGA, Lagos, Nigeria. as presented in Figure 12, Alimosho LGA is situated in the Lagos state, in the southwest region of Nigeria. Lagos is divided into five Administrative Divisions (Lagos, Epe, Badagry, Ikorodu, and Ikeja) which are further divided into 20 Local Government Areas (LGAs) and 37 Local Council Development Areas (LCDAs). The Lagos Metropolitan Area also known as Metropolitan Lagos contains about 85% of the population of Lagos State, and includes semi-rural areas K.E. Enongene, et al (2021). Alimosho LGA, the selected area for this study is the largest LGAs out of the 16 LGAs in Metropolitan Lagos, considering the 2006 Population and Housing Census (National Population commission Nigeria, 2006), and is located at 06°34′5″N 3°15′4″E.

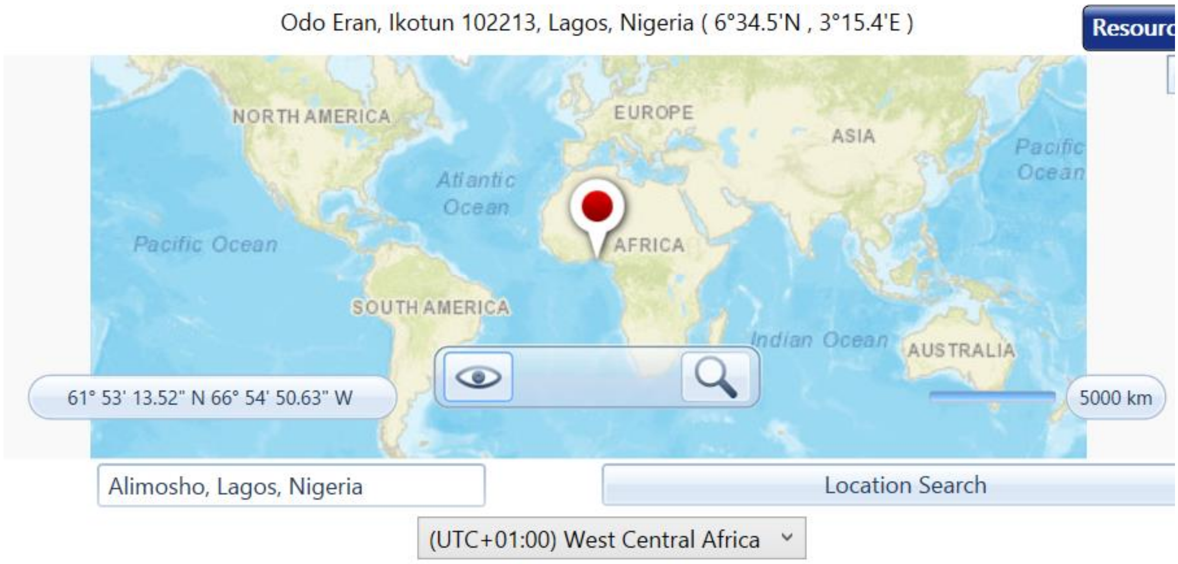

Figure 12: Precise location Odo Eran, Ikotun, in Alimosho LGA, Lagos, Nigeria

Jiboye (2014) reported five categories of residential buildings in Nigeria: duplex, single-family bungalow, a traditional courtyard, flat/ apartment dwelling, and 'face-me-I-face-you'. Out of these five categories of buildings, the apartment and duplex types were considered for this study. The study consists of a total of 50 households (10 per building type) that were randomly sampled in Alimosho LGA by K.E. Enongene, et al (2021). Most of the population living in Alimosho LGA face existing challenges, such as unreliable power supply from the grid. The households were selected based on the area's electricity access situation and the economic condition of the dwellers to pay for the services in different households. Table 1 indicates the profile of the selected location and its focus.

Table 1: Profile of the selected location and its focus

Details	Description
Focus of study	Urban residential households
Year the location was established	1945
Name of the area of study	Alimosho LGA
Number of Households	50
Access to electricity	Limited and insufficient power supply
Region	Southwest
Location	Latitude 06°34′5″N 3°15′4″E
Country	Nigeria

4.2 Sizing of Stand-alone solar PV-system

4.2.1 Electrical Load profile computation

Primary data for each household electrical load was obtained from K.E. Enongene, et al (2021). The load profile of apartment and duplex building types respectively was gathered during a comprehensive site survey conducted by the researchers K.E. Enongene, et al (2021). The power rating and quantity of the usual electrical appliances used in each household were recorded and the typical period of operation was audited. The load assessment was done by calculating the power rating of the usual electrical appliance, the total quantity of appliances, and the hours of operation. The daily load profile for each household was obtained as an average of the load profile for the seven days of the week.

4.2.2 System Design with Homer Pro

A stand-alone PV system was designed to meet the minimum and maximum load profile for apartment and duplex building types in Alimosho LGA. A total of 2 PV system was designed in this regard 1 for the minimum load profile and the other for the maximum load profile. To initiate this design, the solar resource data of the specific location in Alimosho, Lagos, Nigeria which coordinated at 06°34′5″N 3°15′4″E, the minimum and maximum electric load profiles, technical and cost details of solar PV system components (PV array, battery, and Inverter). were implemented in Homer Pro.

For this study, Hybrid Optimization Model for Electric Renewable (HOMER) software is utilized to model and size the solar PV power system. HOMER is utilized to accomplish three tasks: simulation, optimization, and sensitivity analysis, as shown in Figure 13. (Yorke & Woenagnon, 2021). HOMER was selected because it is the most widely used software to design, and analyze renewable energy systems (Okedu & Uhunmwangho, 2014). HOMER's optimizing function estimates several PV system scenarios, and its optimization and sensitivity analysis algorithms determine several possible system configurations (Okedu & Uhunmwangho, 2014).

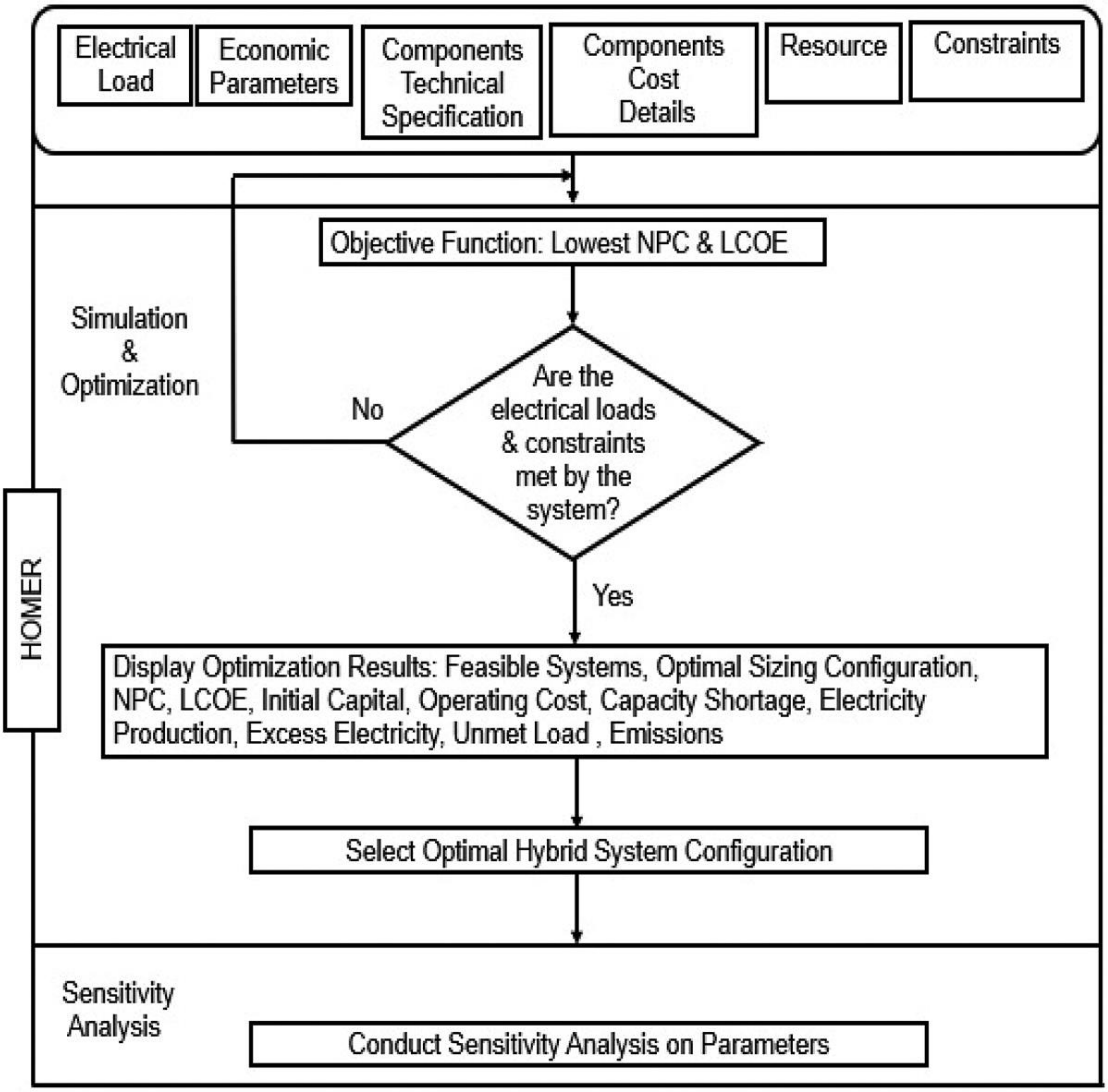

Figure 13: Steps utilized in HOMER Pro software (Yorke & Woenagnon, 2021)

During the simulation, Homer models the system by running each system configuration for one year to determine the system that meets the technical constraints assigned to it. In the optimization, HOMER decides the most cost-effective way to meet the electric load under technical, economic, and system conditions. Sensitivity analysis helps to investigate the impact of variation in input parameters on system performance (HOMER Energy, 2021). In this work a sensitivity analysis was performed with the following parameters: PV-system lifetime maximum, inflation, and discount rate to evaluate their effect on the system's LCOE, annual capacity shortage, and minimum battery SOC. Table 2 presented the used sensitivity parameters. The base case scenario calculation was done based on the following conditions.

The capacity shortage was set at 0% to trace the potential of the PV system to supply the households' load, while a minimum battery state of charge of 30% was used to safeguard its lifespan. Other used parameters include a 10% discount rate, 10% inflation rate, and a PV-system lifetime of 25 years.

Table 2: Sensitivity parameters employed in the HOMER Pro modeling.

sensitivity variable	Sensitivity case(s)
Maximum annual capacity shortage	0%, 5%, 10%
Discount rate	10%, 15 %
Pv-system lifetime	20years, 25years, 30years
Inflation rate	10%, 15%
Minimum battery soc	30%, 40%

4.3 System component specifications and cost details

HOMER uses the following equation 1 to compute the output of the PV array.

$$P_{PV} = Y_{PV} f_{PV} \left(\frac{G_T}{G_{T,STC}} \right) \left[1 + \alpha_P \left(T_c - T_{c,STC} \right) \right] \quad (1)$$

Where Y_{PV} is the rated capacity of the PV array (kW) under standard test conditions (STC),

f_{PV} is the PV module derating factor (%),

G_T represents the incident solar irradiation on the PV panel in the current time step (kW/m2),

$G_{T,STC}$ is the incident solar irradiation at standard test conditions (1 kW/m2), α_P represents temperature coefficient of power (%/^{o}C),

T_c represents PV cell temperature (^{o}C), and

$T_{c,STC}$ is the PV cell temperature under STC (25^{o}C).

This study considered costs that included the initial capital, replacement cost, and operating and maintenance (O&M) cost of the PV array. Globally, the cost of PV panels has declined drastically over the years due to advancements in solar cell efficiency and the rate at which new projects are being commissioned at a low absolute cost level (IRENA, 2019). Currently, local, and foreign companies exist in the Nigerian market supplying PV systems. The cost of PV system components was obtained from a local supplier in the market. The average cost of PV panels with accessories was estimated at 663 USD/kW. A 10% margin for installation was added, increasing the PV capital cost to 730 USD/kW. Furthermore, the PV replacement cost is 0 USD/kW since the PV lifetime equals the project lifetime. The operation and maintenance costs are 6 USD/kW/year, for cleaning the PV panels.

For this study, a PV derating factor of 0.9, as adopted from C.P Cameron, et al. (2008) was applied to compensate for reductions in efficiency due to temperature, dust, shading, and wiring losses. A typical PV panel lifespan of 25 years is considered. PV arrays were mounted at a fixed angle with a slope of 6º which was found to be optimal for the proposed location. (Jacobson, and Jadhav, 2018). Furthermore, ground reflectance, which accounts for the percentage of solar radiation reflected, is taken to be 20%, while the cell temperature TC was adopted from Caisheng and Nehrir (2008) as 80%.

The diesel generator uses diesel to produce electricity. The fuel slope defines the volume of diesel consumed by the generator to generate electricity. HOMER calculates the fuel consumption rate for that time step using equation (2).

$$F = F_0 \cdot Y_{gen} + F_1 \cdot P_{gen}$$

(2)

Where F is the fuel consumption rate this time step [L/hr.],

F_0 represents the generator fuel curve intercept coefficient (L/h/kWrated),

F_1 is the generator fuel curve slope [L/hr/kWoutput]

Y_{gen} is the rated capacity of the generator (kW) and

P_{gen} represents the output of the generator in this time step (kW).

The supply and installation cost for diesel generators was obtained from notable local suppliers. Based on information obtained from the supplier, the diesel generator capital cost is about 250 USD/kW. The replacement and O&M costs are about 250 USD/kW and 0.08 USD/h/kW. The price of diesel fuel in the Nigerian market was about 0.619 USD/L (GlobalPetrolPrices, 2021) during this study. However, a 10% margin to cover the transportation and delivery costs increased the price to 0.680. USD/L.

4.3.1 Battery and power converter

The battery bank stores energy produced from solar PV systems. This energy meets the electrical loads when there are power outages from the grid or backup option. The battery bank autonomy and battery lifetime are very critical parameters when sizing the battery bank capacity.

HOMER computes the battery bank autonomy using equation 3.

$$A_{batt} = \frac{N_{batt} V_{nom} Q_{nom} \left(1 - {q_{min}}/{100}\right)(24h/d)}{L_{prim,ave}(1000Wh/kWh)} \qquad (3)$$

A_{batt} represents battery quantity,

N_{batt} is the number of batteries in the storage bank.

V_{nom} represents the nominal voltage of single storage (V),

Q_{nom} is the nominal capacity of single storage in (Ah),

q_{min} is the battery bank's minimum state of charge in %, and

$L_{prim,ave}$ is the average primary load in kWh/d.

The cost of a battery in the local market is about 165 USD/kWh (Battery (deep acid lead, 83.3 Ah)). Hence, a 10% margin for installation was added, increasing the capital cost to 181 USD/kWh. Also, the battery replacement cost is taken into consideration. Proper operating and maintenance (O&M) cost of 5 USD/kWh/year is considered. Although Li-ion is the best option, the affordability for the households in the region must be considered. Most of the households already using PV systems cannot afford the Li-ion battery due to its higher initial cost.

The converter is a device that converts DC output from the PV system to AC output to meet the household AC loads. The converter has an efficiency of 95% and a lifespan of 15 years. A converter's cost in the local market is about 163 USD/kW. A 10% margin for installation increased the capital cost to 179 USD/kW.

To simulate the PV system and optimize the size of each component, HOMER needs some technical features and the cost of each component. For this, Table 3 lists the technical specifications and costs of all components employed in the system.

Table 3: Technical specifications and costs of the components.

Component	Model (Abbreviation)	Technical Specifications	Capital Cost	Replacement Cost	O&M Cost
PV	Jinko Eagle PERC60 300W (Jinko60/300)	Rated capacity: 0.3 kW Lifetime: 25 yr Electrical bus: AC Derating factor: 90% Temperature coefficient: −0.39%/°C Operating temperature: 45 °C Efficiency at standard test conditions: 18.3% Ground reflectance: 20% Tracking system: no tacking Panel type: flat plate	730 ($/kW)	0 ($/kW)	6 ($/kW/yr)
Battery	Generic 1kWh Lead Acid (1kWh LA)	Nominal voltage: 12 V Nominal Capacity: 1 kWh Maximum Capacity: 83.4 Ah Capacity Ratio: 0.403 Roundtrip efficiency: 80% Maximum charge current: 16.7 A Maximum discharge current: 24.3 A Initial state of charge (SOC) in (%) 100 Minimum SOC in (%) 40 Lifetime: 10 yr	181 ($/kW)	181 ($/kW)	5 ($/kW/yr)

		String size 1 Cycle life @ maximum DOD 800			
Battery	Generic 1kWh Li-Ion (1kWh LA)	Nominal voltage: 6 V Nominal Capacity: 1 kWh Maximum Capacity: 167 Ah Roundtrip efficiency: 90% Maximum charge current: 167 A Maximum discharge current: 500 A Initial state of charge (SOC) in (%) 100 Minimum SOC in (%) 20 Lifetime: 15 years. String size 2 Cycle life @ maximum DOD 3000	545 ($/kW)	475 ($/kW)	0($/kW/yr.)
Converter	System converter (Converter)	Lifetime: 15 years. Rectifier efficiency: 95% Rectifier relative capacity: 100% Inverter efficiency: 95%	179 ($/kW)	179 ($/kW)	10 ($/kW/yr)
Genera	Auto size Genset (Gen)	Fuel: Diesel fuel curve intercept: 0.615 L/hr. fuel curve slope: 0.615 L/hr./KW Emissions CO (g/L fuel): 16.5	250 ($/kW)	250 ($/kW)	0.08 $/h/kW

t o r		unburned HC (g/L fuel): 0.72 Particulates (g/L fuel): 0.1 Fuel Sulfur to PM (%): 22 Lifetime hours 15000			

4.4 Economic analysis

HOMER Pro was employed in conducting the economic analysis using the information presented in Table 3. The Levelized Cost of energy generated by the system using a 10% inflation rate and 10% discount rate was determined. The operation and maintenance cost were considered as 2% of the initial PV-system module cost while the installation cost of the system was considered as 10% of the initial PV-system module cost.

4.4.1 Net present cost (NPC)

In HOMER, the system life-cycle cost is represented by the total net present cost (NPC). The NPC comprises of initial capital cost, replacement cost, annual operating, and maintenance cost as well as fuel costs

NPC is expressed in Equation (4).

$$C_{NPC} = \frac{TAC}{CRF(i,N)} \quad (4)$$

where TAC is the total annualized cost ($/year) and

CRF, the capital recovery factor is a function of the annual real interest rate

(*i*), and the project lifetime

(*N)* in years.

CRF is given in Equation as:

$$CRF(i,N) = \frac{i\,(1+i)^N}{(1+i)^N - 1} \quad (5)$$

4.4.2 Levelized cost of energy (LCOE)

The levelized cost of energy is defined as the average cost per kilowatt-hour of useful electrical energy produced by the system. HOMER uses Equation (6) to calculate the Levelized cost of energy.

$$COE = \frac{TAC}{E_{anloadserved}} \quad (6)$$

Where $E_{anloadserved}$ is the total annual load served by the system in kWh.

5. Results and Discussion

5.1 Energy Consumption in Buildings

The evaluation of a building's energy performance is essential to ascertain the efficiency of energy use, as well as the benchmarking of carbon dioxide (CO_2) emitted in such buildings (P.O.Oluseyi et al, 2016). The sources of energy for all the urban residential buildings in the selected area of study were found to be electricity from the grid, which is usually insufficient, and direct fuel combustion. The direct fuel used included petrol/diesel generators as they are mostly used as a backup solution during grid electricity outages. However, Nigeria has abundant renewable energy sources which have been identified by several studies assessing the potential for the use of solar energy, wind energy, biomass, and hydropower (Shaaban & Petinrin, 2014). According to Homer, the solar daily radiation for this precise location Odo Eran, Ikotun 102213, in Alomsho LGA, Lagos, Nigeria, shows values ranging from 3,950 kWh/m^2/day for July (lowest solar radiation) to 5,490 kWh/m^2/day for February (highest solar daily radiation), as presented in Table 4. Additionally, Nigeria has large reserves of conventional non-renewable energy sources including natural gas, crude oil, coal, and tar sands (C.O Okoye et al, 2016)

The identified energy end-uses in the study location were lighting, cooling, cooking, household appliances, and water pumping. Lighting includes mainly the use of fluorescent lamps and compact fluorescent bulbs. The cooling in the study area involved the use of air conditioners and was found to have higher power ratings. The energy used for cooking in the study area involved the use of electricity (hot plate, microwave, oven, boiling ring, electric kettle, rice cooker), kerosene, and LPG cookstoves, as collaborated by K.E. Enongene, et al (2021). The choice of the source of energy used for cooking in Lagos State, Nigeria is influenced by the level of income, and education of the individual Emagbetere et al. (2016). The household appliances involved mainly the use of television and refrigerators, being the most widely used appliances in the study area. High energy consumption from luxurious and high-power rating electrical appliances are prevalent with urban dwellers like those in Lagos city compared to rural dwellers (Olaniyan et al., 2018).

The average weekly consumption of diesel in the study location for apartment buildings is 12 liters compared to 14 liters used in duplex buildings. The energy consumed in the study area differs during seasons, due to the influence of meteorological parameters on the daily electricity load of different households as collaborated by Fotsing et al. (2014) who reported the occurrence of minimum load in August (wet season) and maximum load in the month December (hot season) in Cameroon and Aldossary et al. (2014) who reported the need of more electricity for air conditioning during periods of higher temperatures.

Table 4: Daily Solar radiaton for every month in Alimosho LGA.

Month	Daily Radiation(kW/m²/day)
Jan	5.280
Feb	5.490
Mar	5.460
Apr	5.210
May	4.760
Jun	4.040
Jul	3.950
Aug	3.980
Sep	4.090
Oct	4.550
Nov	4.950
Dec	5.170

The electric load demand for the minimum load of the apartment building type resulted at an average of 5.79 kWh/day with a peak load of 1.3 kW_p, as presented in Figure 14. The maximum load of the duplex building type resulted at an average of 36.72 kWh/day with a peak load of 9.19 kW_p, as presented in Figure 15.

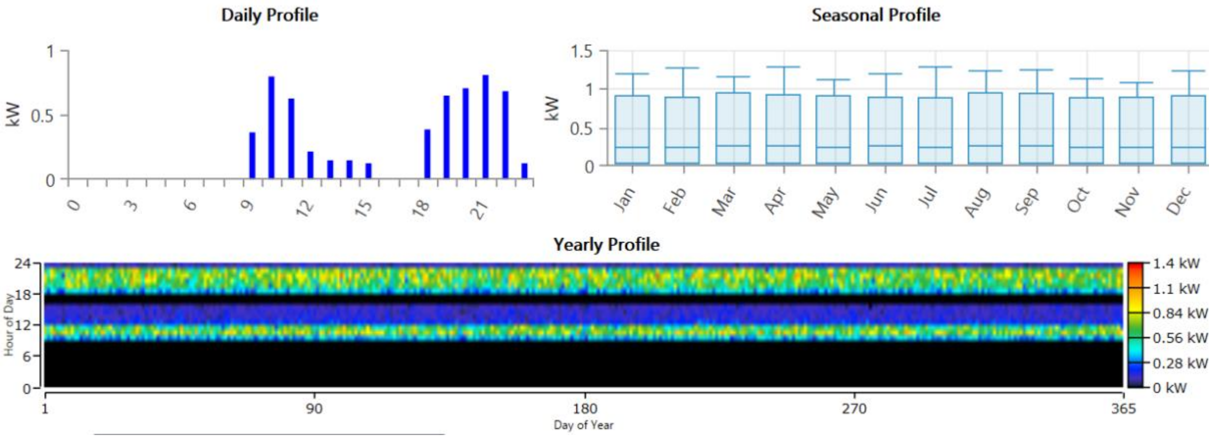

Figure 14: The daily profile, seasonal profile, and yearly profile for the minimum load of the apartment building

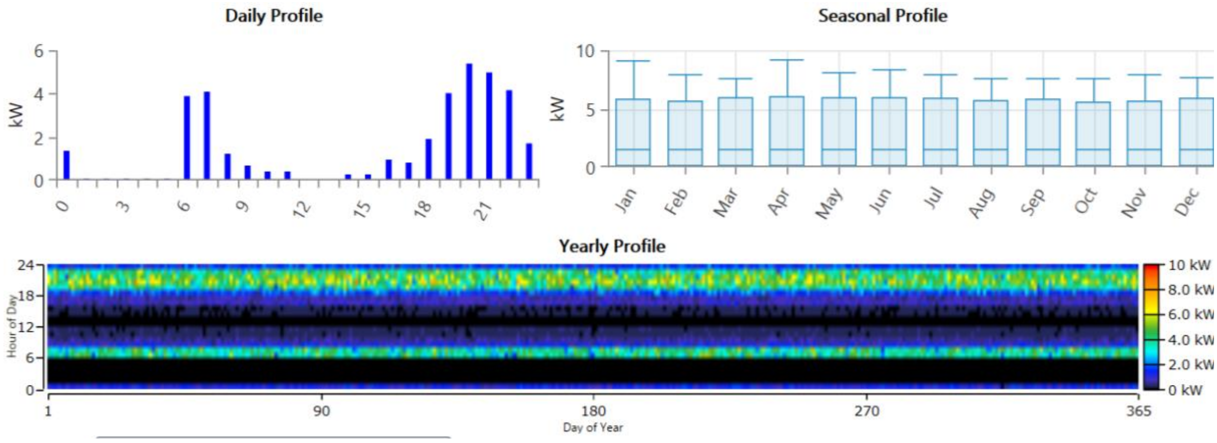

Figure 15: The daily profile, seasonal profile, and yearly profile for the maximum load of the duplex building

5.2 Optimal Design of the PV-system for maximum and minimum loads of buildings

The roof space accessible for the whole of Nigerian urban residential structures is projected to be the product of the net-available roof surface and the total number of appropriate urban roofs, which results in 796 km^2 (NERC, 2017). This figure reflects roughly 5% of Nigeria's total urban surface area and less than 1% of the country's overall land surface (NERC, 2017).

Nigeria's roof-mounted solar technological potential for residential urban structures has been estimated at 124 GWp (Singh et al.,2020). This figure is almost 10 times the nation's existing power generating capacity (12.52 GW). Although solar PV has a lower capacity use factor compared to conventional energy sources, energy output from rooftop PV's projected technological capability would be substantially more than Nigeria's present generating capacity. Therefore, this study shows that Nigeria has a reasonably large rooftop solar power potential. When rural homes are factored in, the anticipated potential grows even more.

Although the rooftop solar system of urban areas in Nigeria utilizes a smaller portion of its projected technological capacity, it is likely to replace a set of gasoline and diesel generators which families apply for backup. Furthermore, because the overall number of homes is calculated based on the entire population, this amount is projected to rise in the coming years as the inhabitants, urbanization, and the creation of more modern technology, grow (Jo et al., 2017). Moreover, rooftop solar systems allow for various uses of land, which is a highly limited resource, particularly in metropolitan regions (Jo et al., 2017).

The optimization results of the HOMER Pro simulations from the considered technical specifications, the result of the proposed system determined was a system with the maximum annual capacity shortage of 0%, battery minimum state of charge of 30%, PV-system's lifetime of 25 years, a discount rate of 10%, and an inflation rate of 10%. are presented in Table 5. The proposed system is simulated by considering the technical specifications as follows:

- maximum annual capacity shortage (0%, 5%, and 10%),
- battery minimum state of charge (30%, 40%),

- PV-system's lifetime (25 years, 20 years, and 30 years),
- Discount rate (10%, 15%)
- Inflation rate (10%, 15%).

Table 5: Optimization results of simulating the models.

LGA	PV-system array (kW)	Lead-acid battery (kWh)	Converter (kW)	LCOE ($)
Alimosho	PV-SYSTEM DESIGN FOR MINIMUM LOAD OF FLAT APARTMENT BUILDING			
	4.03	17	1.41	0.265
	PV-SYSTEM DESIGN FOR MAXIMUM LOAD OF DUPLEX BUILDING			
	32.7	132	9.56	0.350

For the optimal designed solar PV systems for meeting the minimum load of the apartment building type, a 4.03 kW PV array will be required for such building type in Alimosho LGA, with a 17 kWh lead-acid battery for the energy storage unit and a 1.41 kW converter. On the other hand, the solar PV system designed for the maximum load of the duplex building type in Alimosho LGA will require a 32.7 kW PV system array, with a 132 kWh lead-acid battery for the energy storage unit and a converter of 9.56 kW. The PV system components vary regarding the electric load demand of the different building types. The most optimal result of the system considered is ranked based on the total NPC and LCOE.

According to Homer pro, the system with optimal design generated electricity was at 6342 kWh/yr., whereas 3775 kWh/yr. was generation surplus, which means that 59.5% of the energy generated was not utilized. This is due to the mismatch with the demand and lack of storage capacity, as well as the unavailability of options to inject it into the grid. The cost of energy generated by such a system is 0.265 USD/kWh. In addition, the battery autonomy was 49.4 hours, which indicates that the battery can run for 2 days after reaching its maximum state of charge.

As for the system designed for the maximum load of the duplex building, a 32.7 kW PV array and a 132 kWh lead-acid battery for the energy storage unit and a converter of 9.56 kW. In a year, 48893 kWh was generated, whereas 64.7% of this energy was damped. The cost of the energy generated by the system is 0.35 USD/kWh. which means that the battery was well used compared with the previous case. The number of hours at which the system cannot meet the load demand was 199 hours, which translates to 2.2% of a year.

The summary of the technical results of analyzing the 2 proposed system designs using the specified parameters is depicted in Table 6.

Table 6: The summary of the technical results of analyzing the 2 proposed system designs

Quantity	Min Load for Apartment	Max Load for Duplex
Total electricity production (kWh/yr)	6,342	48,893
Excess electricity (kWh/yr)	3,775	31,640
Unmet electric load (kWh/yr)	7,85	8.04
Maximum Output KW	43.9	43.9
AC Primary Load	12,234	13,395
The share of excess electricity (%)	59,5	64.7
Capacity Shortage (kWh/yr)	11.09	13.2
Autonomy (hr)	49.4	51.8
Expected Life(yr)	8.94	8.88
Storage Depletion (kWh/yr)	26.5	28.2
Loses (kWh/yr.)	2,231	2,657
Capacity factor of PV (%)	16.5	16.8
Energy In (kWh/yr)	11,254	13,269
Energy Out (kWh/yr)	8,722	10,640
Capacity factor of Inv (%)	10.8	12,1
Hours of Operation hrs/yr	4,886	4,316
CO_2 emission (kg/yr)	0	0

5.3 Sensitivity analysis for technical specifications for system components

A sensitivity analysis was conducted on the minimum battery state of charge (30%, 40%) and the annual capacity shortage (0%, 5%, and 10%). The effect of varying minimum battery state of charge and annual capacity shortage on the technical specifications of the PV system designed for the minimum load of the flat apartment building type is presented in Table 7.

Table 7: Effects of minimum battery state of charge and capacity shortage on system components (for minimum loads of flat apartment building type)

Building Type	Sensitivity value (%)	PV-system array (kW)	1 kWh lead-acid battery	PV-system power output (kWh/year)
Sensitivity variable: Minimum battery state of charge				
Flat-apartment	30%	4.03	17	6342
	40%	4.74	17	7 454
Sensitivity variable: Maximum annual capacity shortage				
	0	4.03	17	6 342
Flat-apartment	5	2.98	9	4 695
	10	2.61	7	4 099

The battery state of charge (SOC) variations for the two proposed systems are presented in Figure 16 and Figure 17. The result shows that the operating SoC is kept within the specified limit of 30% –100%. July and August are found to be months with the highest use of the battery.

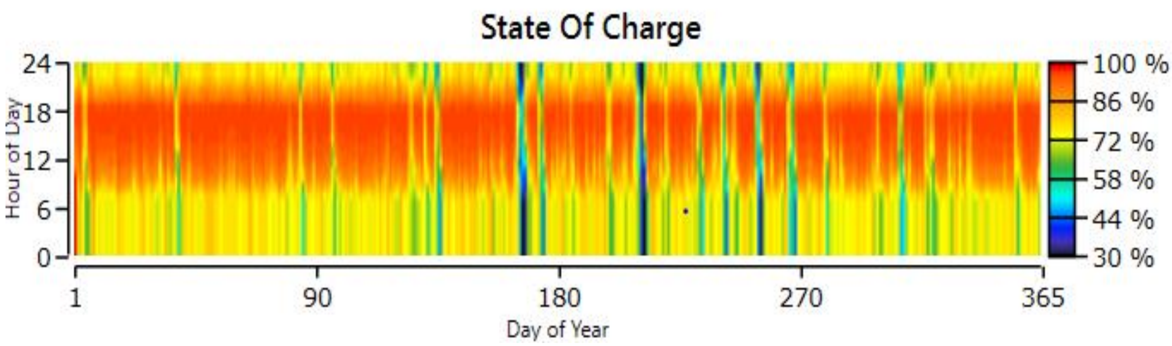

Figure 16: SoC output of lead-acid battery for the minimum load of the apartment building.

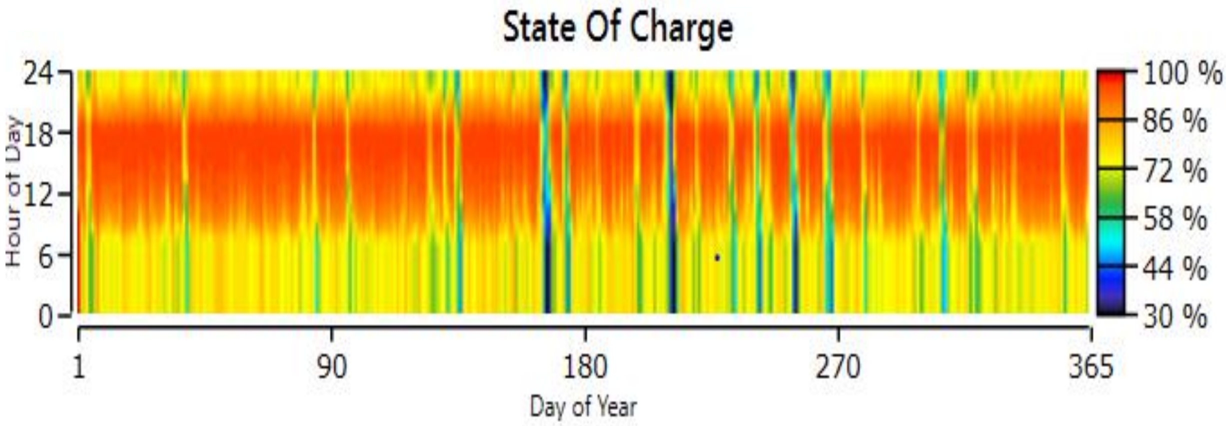

Figure 17: SoC output of lead-acid battery for the maximum load of the duplex building

The results of the sensitivity analysis show that increasing the minimum battery state of charge from 30% to 40% will lead to an increase in the size of the PV system array to 4.74 kW while the lead-acid battery remains at 17 kWh with the autonomy decreasing to 42.4 hr. The change of minimum battery state of charge (from 30% to 40%) will increase the PV production which in turn leads to a surplus generation that will not be required by the designed system. This surplus generation occurs when the battery is fully charged and discharges less than expected. This occurs mainly from 10:00hrs to 14:00hrs daily, because at that time the solar radiation is at its peak (A. A Mas'ud, 2017).

An increase in the maximum annual capacity shortage (from 0% to 10%) will lead to a decrease in the size of the PV-system array to 2.61kW and the lead-acid battery to 7 kWh, respectively. As pointed out by Givler and Lilienthal (2005), an increase in capacity shortage can significantly improve the competitiveness of PV/battery systems and decreases the amount of the load of the building that must be met by the system and consequently, a reduction in the PV- system array and battery bank. At 0% capacity shortage the unmet electric load was 1.75 kWh/yr., but when increased to 5% capacity shortage the total production dropped to 4695 kWh/yr., leaving the system with an unmet electric load of 78.2 kWh/yr. A capacity shortage of 10% produced the lowest electricity generation, of 4,099 kWh/yr. and an increased unmet load of 152 kWh/yr. The results of the impact of an increase in the capacity shortage from 0% to 10% on the lead-acid battery state of charge and the unmet load for the apartment building type are presented in Figures 18a, b, and c respectively.

Figure 18(a): The effect of an increase in the capacity shortage of 0% on the lead-acid battery state of charge and the unmet load for the apartment building type

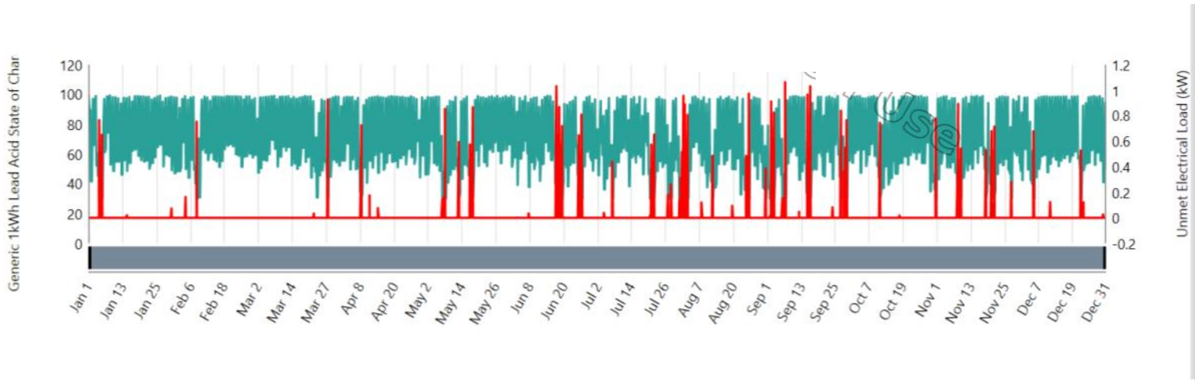

Figure 18(b): The effect of an increase in the capacity shortage of 5% on the lead-acid battery state of charge and the unmet load for the apartment building type.

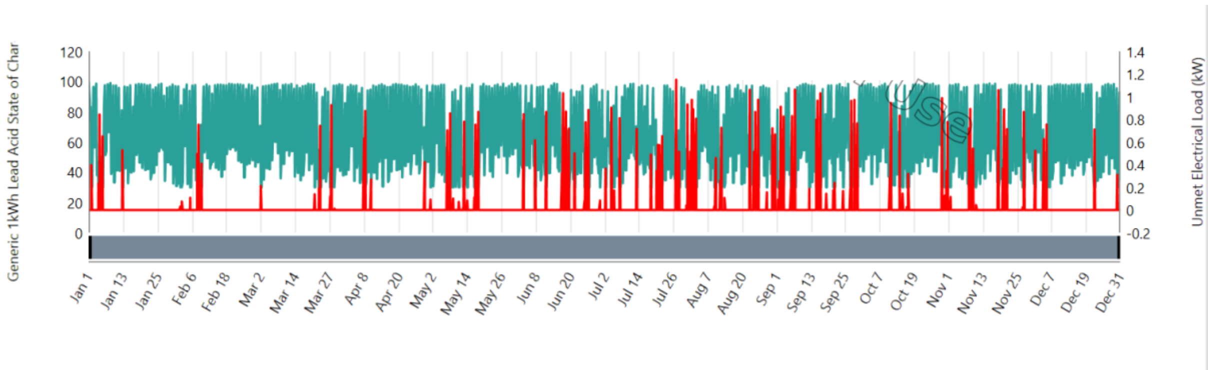

Figure 18(c): the effect of an increase in the capacity shortage of 10% on the lead-acid battery state of charge and the unmet load for the apartment building type.

5.4 Economic analysis

The economic analysis results of the rooftop PV systems regarding the LCOE for the proposed system are presented in Table 8. The LCOE for the designed systems for the minimum load (flat apartment) was 0.265 USD/kWh and the maximum load (duplex building) was 0.350 USD/kWh. The LCOE varies because there is a difference in the loads of the buildings. The approved average electricity tariff for the grid power system in some locations in Nigeria is about USD 0.10/kWh, as of September 2021 (Resagratia, 2021). Therefore, the values of the LCOE generated from the PV systems are more expensive than the average current tariff (0.10 USD/kWh) paid by urban dwellers in Alimosho LGA.

Table 8: Results of the economic analysis of the PV systems.

LGA	Building type	LCOE (USD/kWh)
Alimosho	Duplex (maximum Load)	0.350
	Flat apartment (minimum load)	0.265

This reinforces the assertion of Opiyo (2016), that the general cost of PV systems in sub-Saharan Africa is higher than it is in developed nations. This makes even the most basic of PV systems out of reach of most residents and thus hindering adoptions from an economic and financial standpoint since most households are unable to afford the initial capital of the system due to low income.

Key observations can be gleaned from similar studies that incorporate designed PV systems. The LCOE presented by the 2 designed PV systems of 0.265 USD/kWh and 0.350 USD/kWh is comparable to the LCOE obtained for the city of Lagos (0.417 USD/kWh and 0.495 USD/kWh) for a study conducted by Okoye et al. (2016). Although this study considered all the components of a stand-alone PV system as the same with the study conducted by Okoye et al. (2016), their study utilized an estimated electricity load profile of a typical large household in Nigeria in the simulation to design the PV- system, while in this case study, household-specific electricity load data for five building types totaling 50 buildings were considered in the simulation of the PV systems using the HOMER Pro software. The significant difference in LCOE is in the past 5 years ago when Okoye et al. (2016) conducted their research the PV cost was higher than the present cost which could have increased the system cost to impact the LCOE.

The results proved that, if the nominal discount rate increased, and the inflation rate declined, the LCOE would increase. For instance, when the discount rate is at 10% and the inflation rate at 15%, the LCOE would be 0.199 USD/kWh, which is less than the optimal PV system at 0.265 USD/kWh. On the other side, when the discount rate is at 15% and the inflation rate is at 10%, the LCOE would increase significantly over the optimal PV system value to 0.346 USD/kWh. Figure 18 presents the surface plot of the variations in Total Net Present Cost, considering the fluctuations of these two rates.

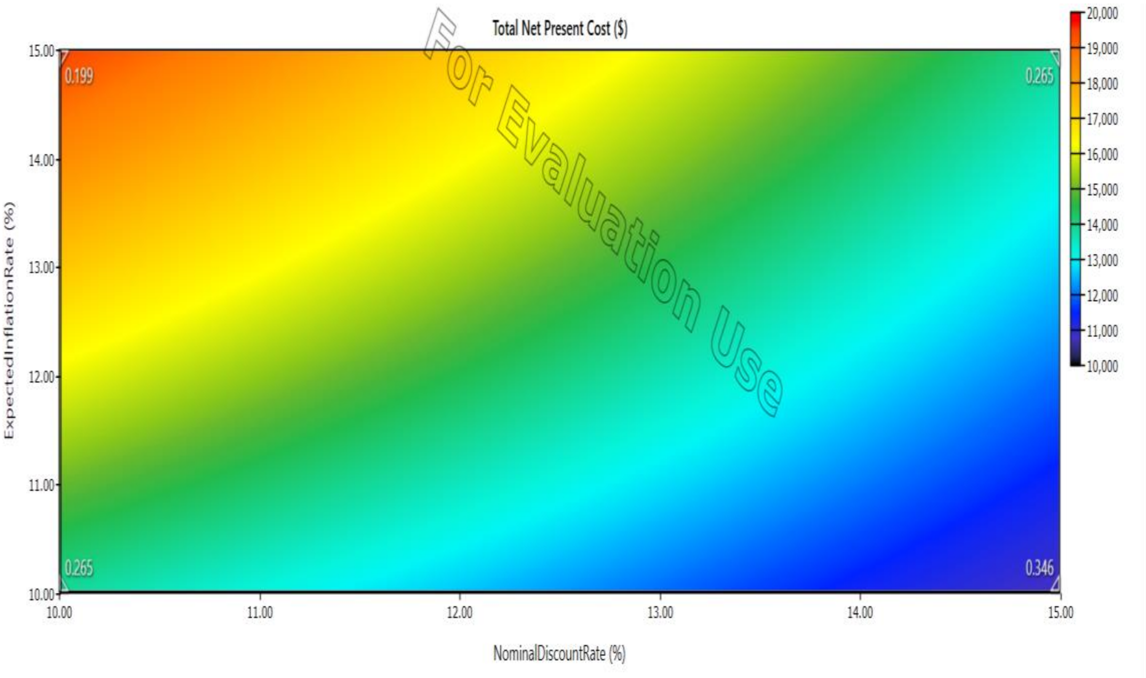

Figure 19(a): Changes of Total Net Present Cost considering the fluctuations of the nominal discount rate and inflation (numbers inside the surface plot refer to LCOE).

Figure 19(b). demonstrates the surface plot of the annual electric production because of the variations in the rates. It can be deduced that, for the case when the discount rate dropped and the inflation rate increased, the electric production would increase and LCOE would be reduced.

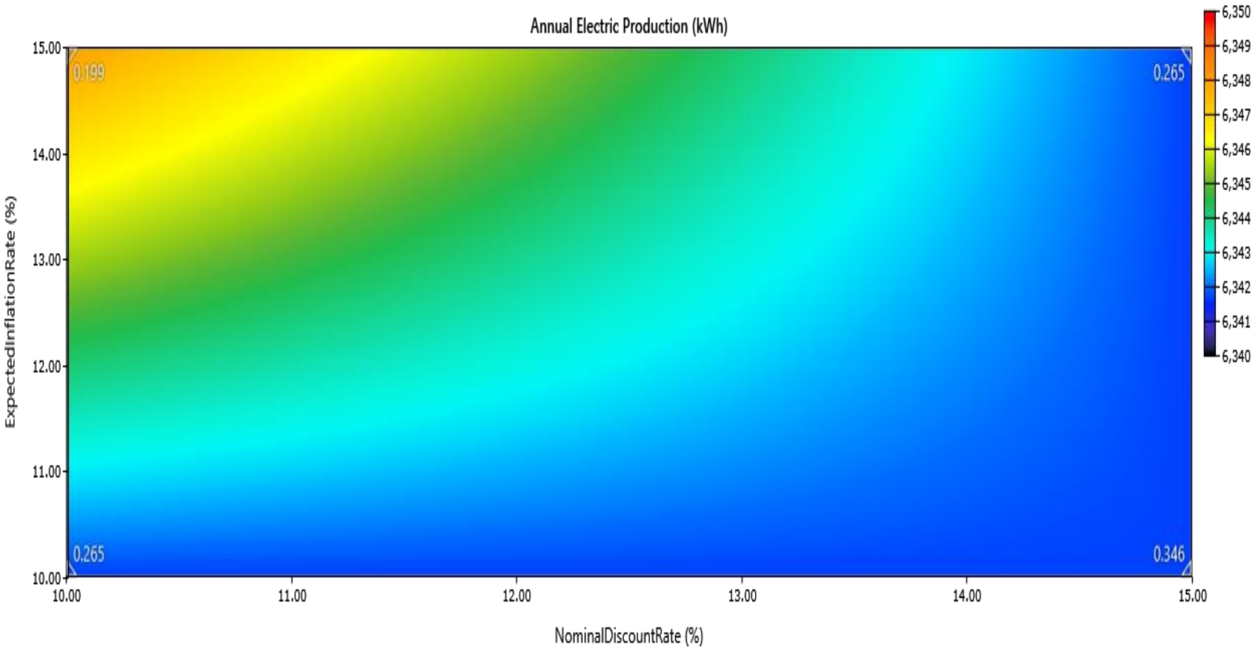

Figure 19(b): Changes of annual electric production considering the fluctuations of the nominal discount rate and inflation (Numbers inside the surface plot refer to LCOE)

Using the duplex building type (maximum load) and the flat apartment building type (minimum load) for the Alimosho LGA, the influence of the discount rate and inflation rate on the LCOE is presented in Figure 20. Increasing the discount rate from 10% to 15% results in an increase in the LCOE while an increase in the inflation rate from 10% to 15% lowers the LCOE. Using the flat apartment building type (minimum load) for the Alimosho LGA as an example, an increase in the discount rate from 10% to 15% results in an increase in the LCOE from 0.265USD/kWh to 0.346 USD/kWh. The LCOE generated from low carbon generation technologies has declined and is gradually becoming lower than fossil fuel generation costs. Also, renewable energy costs have continually declined in recent years (International Energy Agency, 2020). According to Ghenai et al. (2018) when the discount rate increases, the net present value of the PV system is decreased resulting in an increased LCOE of the system.

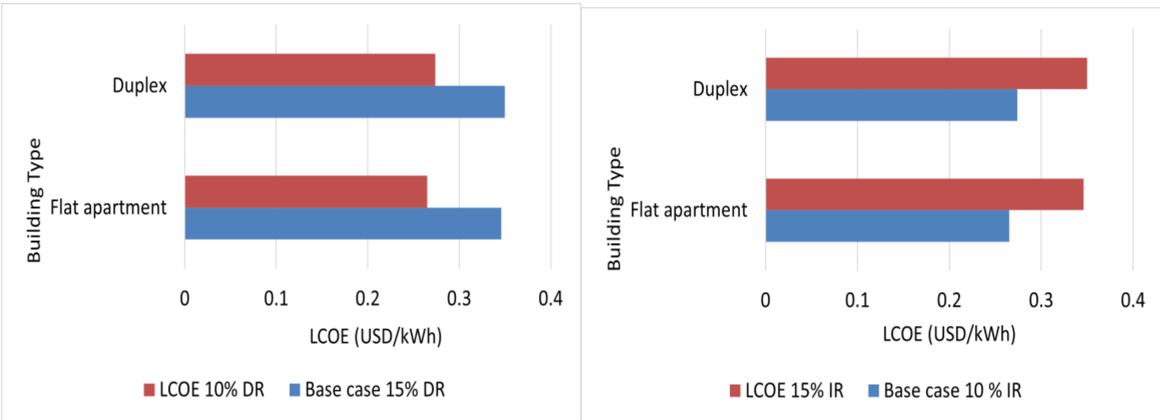

Figure 20: Influence of discount rate (left) and inflation rate (right) on the LCOE for the systems designed for the maximum load for the duplex building type and minimum load for the flat apartment building type.

An increase in the maximum annual capacity shortage decreases the LCOE of the systems. The LCOE for the flat apartment building type (minimum load) for Alimosho LGA decreased from 0.265 USD/kWh (0% capacity shortage) to 0.199 USD/kWh (10% capacity shortage) as represented in Figure 21. Such a reduction in LCOE could be explained by the fact that, as the capacity shortage is increased, the proportion of the building's load to be left unmet increases (such as high load occurring after sunshine hours), and consequently, load demand reduces culminating in a decrease in LCOE of the system is left unserved as collaborated by K.E. Enongene, et al. (2021).

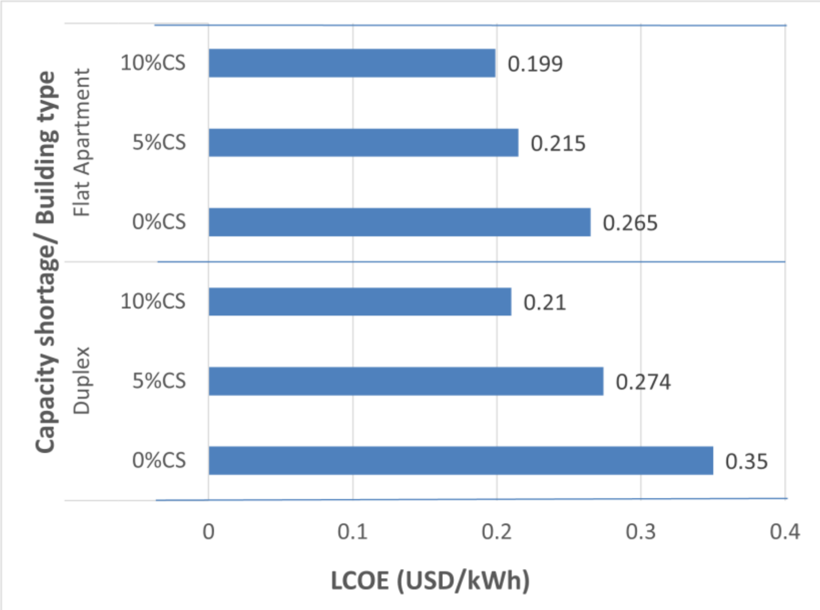

Figure 21: Influence of capacity shortage on LCOE for the minimum load of the flat apartment and maximum load of the duplex.

Regarding the effect on the PV-system lifetime on the LCOE, an increase in the PV-system lifetime is indirectly proportional to the LCOE of the system. A decrease in the PV system's lifetime from 25 years to 20 years is presented in Figure 22 for the case of flat-apartment and duplex building type increases the LCOE of the system while the reverse is said for an increase in the PV-system's lifetime from 25 years to 30 years. As reported by Enongene (2016), an increase in the lifetime of the PV-systems means more energy generated by the system for the same initial capital cost and this explains a decrease in the system's LCOE.

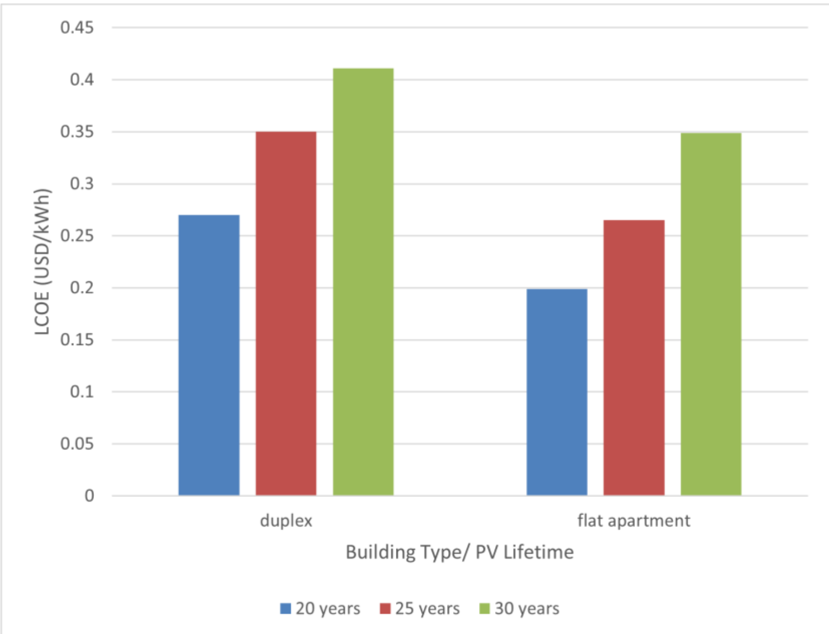

Figure 22: Effect of PV-system lifetime on the LCOE for the system designed for the maximum load for the Duplex building type and minimum load Flat-apartment building type.

5.5 Techno-economic analysis of lithium-ion and lead-acid batteries

An economic and technical analysis of lithium-ion batteries was also conducted by using HOMER-Pro, comparing 1 kWh lead-acid batteries and 1 kWh li-ion batteries with a PV system of 5 kW designed to meet the minimum load of an apartment building. Accordingly, the simulation result of HOMER Pro reveals that the PV system having a lead-acid battery as energy storage requires 17 units of batteries. On the other hand, the system with a Li-ion battery requires only 11 units of batteries. It was observed that lead-acid and Li-ion batteries have almost comparable charge and discharge properties. Besides, from the discharge characteristics, it can be proved that the charge-discharge cycles are comparable for both Li-ion and lead-acid batteries. Furthermore, with a smaller number of cells and less capacity, the discharge characteristics response of Li-ion battery is found to be equal or greater than lead-acid battery providing longer lifetime characteristics, as corroborated by A Kebede (2021). Table 8 presents the cost summary for different components used in the PV system.

Table 9: Cost summary of components of PV optimized system.

Component		**Capital ($)**	**O&M ($)**	**Replacement ($)**	**Salvage ($)**	**Total ($)**
Battery	Li-ion	3,814.00	0	1186.00	-116	4.884
	lead-acid	1.850.00	907.00	3013.00	-82	5.688
Converter with	Li-ion	962.62	25.1	176.62	-19.89	1144.45

	lead-acid	974.48	25.6	178.48	-20.43	1158.13
Total system with Li-ion battery		14,491.89	931.98	1362.31	-133.68	16,651.61
Total system with lead-acid battery		12,537.75	1,839.16	3,191.51	-99.44	17,468.98

The cost elements presented in Table 9 above include the capital, operation and maintenance, replacement, and salvage costs. The capital cost is the total initial cost spend to install the PV system whereas the operation, maintenance, and replacement costs are expenses spent on the operation. It was noticed that the optimized simulation output provides that, the operation and maintenance (O&M), replacement and salvage costs of the lead-acid battery were found to be higher than Li-ion battery under the typical PV systems examined.

The result also established that the PV system together with the lead-acid battery for the storage unit and the PV system together with the Li-ion battery for the storage unit satisfies the total electric load demand. The sufficient capacity of the PV array provides power to the load and hence maintains the battery SoC to admissible limits throughout the operation. Due to the high daily solar radiation availability at the study location where the PV system was designed for the apartment building type, the PV array takes the lead for electricity production throughout the year. The PV system with Li-ion batteries gave a total production of 12,537 kWh/yr., while the PV system with lead-acid batteries gave a total production of 6,834 kWh/yr. The average SoC of Li-ion batteries is illustrated in Figure. 23a, and Figure 23b respectively on an hourly, daily, and monthly basis.

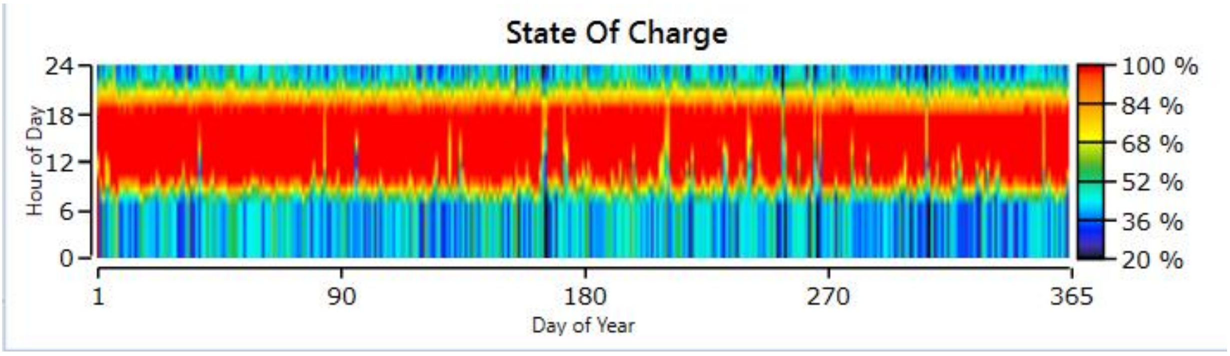

Figure 23(a): SoC output of Li-ion battery Hours of the day vs. day of the year.

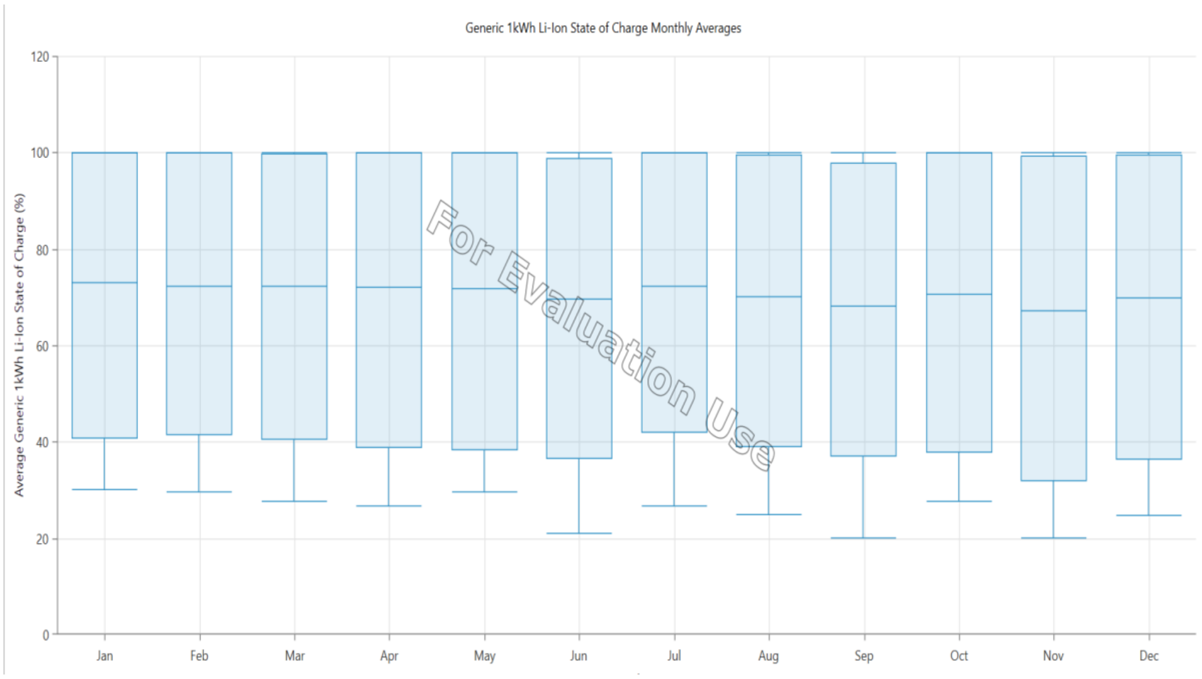

Figure 23(b): SoC output of Li-ion battery SoC vs. month of the year.

As can be seen in Fig 23a, the operating SoC is kept within the specified limit of 20–100%. Besides, the maximum utilization of the battery storage is also observed in September (Figure 23b). Figure 24a below presented the output of the lead-acid battery SoC, showing that the operating SoC is kept within the specified limit of 30–100%. For the case of lead-acid batteries, August and September are found to be months where more electricity has been provided from the battery (Figure 24b).

Figure 24(a): SoC output of lead-acid battery. Hours of the day vs. day of the year.

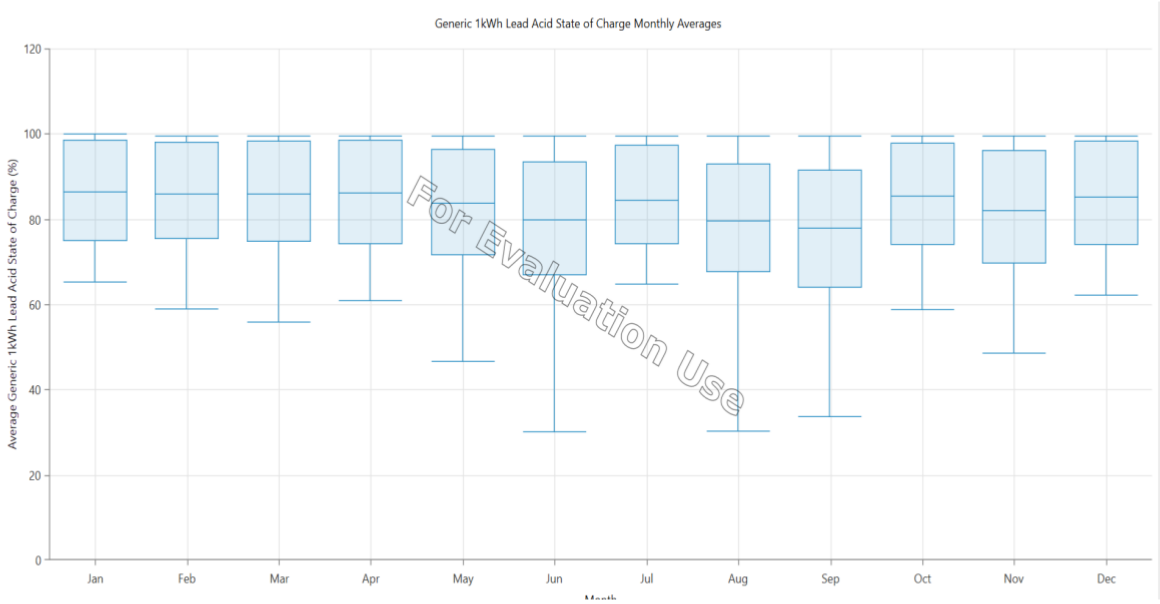

Figure 24(b): SoC output of lead-acid battery vs. month of the year.

The net present cost and cost of energy result of the PV system indicates that the PV system is highly dependent on the type and number of batteries used to store energy. As it is seen from the result in Table 10, in terms of quantity, when Li-ion batteries are used as storage systems, the requirement of batteries is reduced. Similarly, Li-ion batteries have lower lifetime costs than lead-acid batteries when used in PV systems (A.A Kebede, 2021), which in turn resulted in a reduction in the LCOE. The overall study shows that the use of Li-ion batteries as energy storage for PV systems was found to be economical and technically feasible.

Table 10: Comparison of lead-acid and Li-ion batteries based on different performance indicators.

Components	PV (kW)	Number of Battery (units)	Converter (kW)	Total NPC ($)	COE ($)	Operating Cost
System with Li-ion battery	5	11	1.26	16,651.61	0.274	198
System with lead-acid battery	5	17	1.27	17,468.98	0.278	301

On the cost summary of Table 9 and Table10, the net present cost of the system with Li-ion batteries was found to be $16,651.61. On the other hand, the system with a lead-acid battery was around $17,468.98. The total COE is also reduced. The reduction in the COE varies according to the battery energy storage type used in the system. Hence, the PV system with a lead-acid battery provides a COE of 0.265 $/kWh. On the other hand, the PV system with a Li-ion battery provides a Levelized cost of energy of 0.229 $/kWh. However, the initial cost of the PV system with a Li-ion battery is higher compared to the PV system with a lead-acid battery. The adoption of PV systems with Li-ion batteries is still in its initial stages in Nigeria owing to factors such as the income of the dwellers to be able to afford to pay for the PV system with Li-ion battery, due to the higher initial cost.

As illustrated in Table 11, in terms of energy produced, losses, and expected lifetime, Li-ion has a longer life and lower losses, when compared to a lead-acid battery. The reduced losses also lead to the COE reduction of the system with Li-ion batteries. Li-ion batteries are found to be cost-effective when the upfront cost is further divided over the entire operational lifetime. The methods of techno-economic analysis used in this work can further be used for urban residential buildings while considering the resource and demand profiles available at the location to be explored respectively.

Table 11: Energy Storage, Losses, and expected life comparison of lead-acid and Li-ion batteries.

Quantity/Parameters	Li-ion battery	lead-acid battery
Energy In (kWh/Year)	1,369	1,540
Energy Out (kWh/Year)	1,236	1,236
Storage Depletion (kWh/Year)	3.71	4.20
Losses (kWh/Year)	137	308
Annual Throughput (kWh/Year)	1,303	1,382

Expected Life (Year)	15	9.84

5.6 Comparison of the PV-battery system with the diesel generator

The performance of the PV-Battery system designed for the maximum load for the duplex building was further compared with the diesel generator, considering its economic and environmental performance. Comparatively, the designed diesel generator has a lower capital cost than the solar PV system. However, the running cost for diesel generation is much higher than its counterpart Solar PV. Table 12 shows the economic comparison analysis of optimal solar PV system against Diesel Generator system.

Table 12: Economic comparison of optimal solar PV system against Diesel Generator

Parameter	**Technology for electrification**	
Financial Parameter	Solar PV/ System	Diesel Generator
Capital cost ($)	49,908	2,750
Total NPC ($)	117,128.30	435,976
COE ($/kWh)	0.35	1.30
Operating and Maintenance Cost ($)	4,993.27	192,720.00
Operating Cost ($)	2,688.97	17,329.04
Fuel cost ($)	0	203,105.90

From Table 12, the estimated LCOE obtained from the diesel generator is valued at 1.30 USD/kWh. Both of the PV systems designed had a unit cost of electricity lower than 1,30 USD/kWh. Hence, PV-systems LCOE is more cost-effective for use as stand-alone systems compared to diesel generators and urban residential buildings can opt to shift to this technology. Though it has a high initial cost, it is more cost-effective and profitable than diesel generator systems in the long term. While this could establish a reason for the adoption of solar PV, the ability of each household to adopt solar PV depends on the initial capital cost. The LCOE from PV systems obtained from this study could be reduced when the Nigerian government provides an encouraging environment that will strengthen the embracing of the technology.

Diesel generator exhibits significant variation in the cost of the electrical power provided. This results from the changing fuel prices which are hard to predict in 20 years of the project lifetime, as discussed in J.Jurasz et al (2020). Both systems deliver electricity for a price that is more expensive than the grid and would not be accepted by most grid-connected clients. However, such costs are not uncommon in the case of off-grid communities, as presented by M. Guezgouz et al (2019).

As regards the environmental impact, the PV-Battery system is better, since PV systems do not have emissions during the operation, when compared to diesel generators, the diesel-only system provides the highest COE ($1.30/kWh), and emits 31,274 kg of CO_2 per year, leading to adverse effects on the environment. The PV-Battery system is not entirely environmentally friendly due to the significant oversizing of the system and high emissions associated with the construction of the battery. It should be noted that in the case of battery storage systems their environmental impact depends strongly on the country where they were manufactured (structure of their power systems) as reported by J.Jurasz et al (2020).

6. Conclusion and Future Work

6.1 Conclusion

This thesis intended to analyze the technical, and economic potential of rooftop PV systems for electricity generation in urban residential households in Nigeria. Recently, Nigeria has been giving more attention to renewable energy sources to be able to complement the conventional energy sources, in order to meet up the enormous energy demand. In this regard, households are encouraged to generate their own electricity by relying on renewable energy. Technically, PV energy generation is the most suitable system due to the high solar radiation potential in Nigeria.

In this thesis, the techno-economic feasibility evaluation of a stand-alone solar PV system mounted on the rooftop of different urban residential buildings in Alimosho LGA, Lagos (06°34′5″N 3°15′4″E), Nigeria, is presented and analyzed. A sensitivity analysis of the effects of the techno-economic parameters' variation on system performance was considered for the assessment using the Homer Pro software. The results of the proposed PV system size for the minimum load of the apartment building type and for the maximum load of the duplex building type was a PV array (with 4.03 kW and 32.7 kW, respectively), lead-acid batteries (with 17 kWh and 132 kWh, respectively) and the converter of the PV systems (with 1.41 kW and 9.56 kW, respectively).

The results of the economic analysis revealed a LCOE of the systems to be 0.265 USD/kWh for the minimum load of the apartment building type and 0.350 USD/kWh for the maximum load for the duplex building type. Generally, from a technical perspective, stand-alone solar PV systems have the potential to be used as a source of electrical energy to bridge the energy deficiency in urban areas in the different categories of residential buildings in Lagos, Nigeria.

In addition, the techno-economic analysis of lead-acid and Li-ion batteries with the same input parameters integrated with the PV system was performed by using HOMER Pro software. Considering the minimum load for apartment building type, the results revealed the lifetime characteristics of Li-ion batteries were found to be better than a lead-acid battery. Besides, it was found that the discharge characteristics response of Li-ion batteries are better than lead-acid providing a longer lifetime of usable capacity. Therefore, it can be concluded that Li-ion batteries present advantages in PV systems. Accordingly, the system with a Li-ion battery resulted in a LCOE of 0.274 $/kWh compared to the system with a lead-acid battery providing a LCOE of 0.279 $/kWh. On the other hand, the NPC of the system with Li-ion batteries is found to be $16,651compared to the system with a lead-acid battery, resulting in an NPC of $17,468.98.

In general, considering the stand-alone PV systems in this study location, Li-ion batteries are found to be profitable in both technical and economic aspects, and therefore, recommended as an alternate feasible solution to be used as a storage unit for the respective PV systems. However, the initial cost can be a barrier as the initial cost of Li-ion batteries is higher than the initial cost of lead-acid batteries. The results of the comparison between the stand-alone PV system and Diesel generator required to meet the maximum load of the duplex building type revealed a LCOE for the diesel generator to be 1.30$/kWh. Additionally, the approved average electricity tariff for the grid power system in some locations in Nigeria is about USD 0.10/kWh, as of September 2021 (Resagratia, 2021).

The promotion of an enabling environment for the adoption and use of solar PV-system in urban residential buildings will support the progress of Nigeria's pledge to the Sustainable Development Goals (SDG). However, just creating a favorable environment for the adoption and use of PV systems may not constitute a solution to all buildings due to high load demand from some building types. Therefore, the need for the government of Nigeria to use a mix of energy scheme options that can support the deployment and uptake of solar PV systems in the country, while reducing residential energy consumption through the promotion of energy efficiency management schemes and policies.

6.2 Future Work

Future research should replicate this assessment for other regions in Nigeria and for other types of residential buildings. It is also important to investigate periods during the day in which power outages occur and based on this information, explore the possibility of designing a solar PV-system grid-connected hybrid system for the residential buildings which is currently not applicable in Nigeria. Another option would be to replicate this assessment for non-residential buildings such as commercial and industrial buildings. Further investigations on the impact of the dynamic variations of solar electric power generation technology costs will be useful to help establish effective energy management schemes and policies that will orient energy production trends towards green and sustainable energy.

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