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Sizing of a Photovoltaic System for an Urban Settlement in a Flood-Prone Area in Southwest, Nigeria

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Abstract

Introduction: Urban settlements in flood-prone areas are faced with significant challenges in ensuring reliable and sustainable energy access. Being privy to a more secured and consistent electricity supply, still remains a feat to be unraveled in certain regions of the Sub-Saharan Africa like Nigeria.

Objectives: This study aims to present a guided approach on how to size a photovoltaic system for an urban settlement in a flood-prone area tailored to address the persistent power outage challenge so as to make electricity available for residents in such location.

Methods: The data used in this study spans from 2017 t0 2021 and was acquired for a study area located in the Southwest of Nigeria situated in Eti-Osa Local Government Area of Lagos State from the National Aeronautical Space Administration (NASA). Additional research resources utilised include Microsoft Excel and the Hybrid Optimization of Multiple Energy Resources software (HOMER Pro).

Results: The total daily energy consumption per category of apartments (2-Bedroom, 3-Bedroom, and Terrace) were 61.15kWh/day, 41.02 kWh/day, and 284.31 kWh/day respectively. Each category of apartment type, the number of photovoltaic panels needed are 3, 5, 7 and 11 respectively while the storage system needed were 1.1 ,2 with zero environmental impact.

Conclusions: The study demonstrated, via a detailed analysis of an urban settlement in a flood-prone area, how the sizing of a photovoltaic system can be channeled to help meet the energy demands of the residents in such a location by guaranteeing that access to electricity is of limited concern with no environmental issues.

Keywords*: electricity, energy demand, flood-prone area, HOMER Pro, load profile, photovoltaic system, urban settlement, sustainable energy*.

1. Introduction

Despite the fact that a nation's economic advancement solely depends on electricity; being privy to a more secured and consistent electricity supply, still remains a feat to be unraveled in certain regions of the Sub-Saharan Africa and other parts of the world (Amole et al., 2023; Ezekwem & Muthusamy, 2023; Orovwode et al., 2021). With enormous energy potential in developing nations like Nigeria, it is alarming how the country continues to struggle with intermittent electricity supplies and inadequate power facilities, which has plaqued many urban and rural communities leaving them in utter darkness to remain without electricity (Amuta et al., 2023; Bamisile et al., 2020: Sanni et al., 2019). The Southwest region of Nigeria has an average daily solar irradiation that happens to fall within the range of 4 and 6 kWh/m² which makes it a suitable area for the implementation of solar photovoltaic systems (Okedu et al., 2024). Emphasis on how solar energy can be used to address the electricity demands of either on-grid or off-grid has been treated by numerous literature work. For instance, Oyedepo et al. (2018) examined how solar PV can significantly reduce the country's dependence on conventional energy sources as well as carbon emissions by providing decentralized renewable energy systems to underserved rural communities. In Southwest Nigeria, where urban settlements situated in flood-prone areas don't experience power supply, as well as the existing utility grid which is unable to meet the electricity demand; the implementation of a solar photovoltaic system will become handy to alleviate the power outage challenge. By using actual data from a monitoring campaign in Lagos, Nigeria, Babajide and Brito's paper advocated the use of residential solar PV systems in urban communities with an alternative goal to stand out in eliminating or drastically reducing the use of diesel generators, which poses risks to people's health and the environment.

One of the features that is peculiar to the Southwest region of Nigerian is the rampant expansion of urban settlement; though an advantage but is also a disadvantage in a way that during the rainy seasons, these areas are known to experience frequent flooding which eventually causes power outage (Onifade et. al., 2023; Kayaga et al., 2021). This frequent flooding in areas that are prone to flood grows into a much bigger problem as it creates a negative impact on the already existing electrical network that transcends to disrupting livelihoods, leaving many communities without electricity for extended periods (Sholanke et al., 2021; Adeaga et al., 2020). In order to achieve sustainability and minimize carbon emissions, it becomes imperative that a new perspective should be in view towards exploring alternative renewable energy sources (Bello et al., 2021; Oyedepo et al., 2018). Across the globe in areas where there is sufficient solar energy but the power supply is erratic, the use of solar photovoltaic systems is gradually emerging as viable solutions to address the inconsistent power supply and a means to provide a sustainable power source (Owebor et al., 2021). PV systems will be a viable substitute to guarantee energy access in Southwest Nigeria, where urbanization, inadequate electrical grid, and frequent flooding pose a major problem. Interestingly, installing PV systems successfully in flood-prone areas will demand a thorough understanding of energy usage and renewable energy potential (Jamiah et al., 2017). The accurate sizing of photovoltaic systems remains a critical consideration in ensuring that energy demands of the consumers are reliably met. Undersizing may lead to insufficient energy supply, compromising system performance, while oversizing can incur unnecessary capital costs and reduce overall system efficiency. Therefore, a balanced and well-informed sizing approach is essential to optimize both operational reliability and economic viability (Egbon et al., 2018; Mandal et al., 2018; Elmorshedy et al., 2022). Aspects like load profiling, solar irradiation and requirements for battery storage all add up to form the sizing process which has been considered in literature by other authors. According to Quiles et al., (2020), in their work, the main aspects to consider in the sizing of PV systems centres on the type of electrical demand of the consumers, peak load demand, solar energy potential, and the type of energy storage amongst others. The importance of sizing with respect to the design of a 5kVA solar photovoltaic system that will be capable to meet the expected load specifications in the Electronics laboratory of Covenant University was emphasized by Mbaya et al (2022). Additionally, diversity factor was also not left out in their work, highlighting the fact that not all electrical appliances will be used precisely at the same time

2. Objectives

This study aims to present a guided approach on how to size a photovoltaic system for an urban settlement in a flood-prone area tailored to address the persistent power outage challenge so as to make electricity available for residents in such location. The approach involves a detailed analysis of site-specific meteorological data, identification of available renewable energy resources, characterization of residential load profiles across different apartment typologies, and technical evaluation using the Hybrid Optimization of Multiple Energy Resources (HOMER) software. In the Nigerian context, to facilitate sustainable energy solutions that can help in both immediate and long-term challenges, the results obtained from this study is meant to serve as a technical guide to electrical engineers, system designers, and infrastructure planners.

3. Methods

The methodology used for sizing a photovoltaic system for an urban settlement in a flood-prone area situated in Southwest Nigeria is presented in this section. A brief description on the selected area, solar resource assessment, the energy demand assessment which is also known as load profile, the system design and sizing were highlighted. The data used in this study spans from 2017 t0 2021 and was acquired from the National Aeronautical Space Administration (NASA). Additional research resources utilised include Microsoft Excel and the Hybrid Optimization of Multiple Energy Resources software (HOMER Pro). The HOMER Pro software was selected for this investigation based on its accessibility and simplicity. Latitude 6.4482° N and longitude 3.5502° E are the coordinates of the selected location as given by HOMER-Pro and presented in Figure 1. The key steps of the method are presented below.

Figure 1: HOMER Pro representation of the selected location

Selected Study Area

A residential estate situated in Eti-Osa Local Government Area, Lagos State, Southwest of Nigeria, was selected as a case study for the design and sizing of a solar photovoltaic system due to its location within water bodies and its low-lying topography, the reason why it is vulnerable to flood in Lagos State as shown in Figure 2. (Onifade, et. al,. 2023; Obiefuna et al., 2021; NIHSA, 2020).

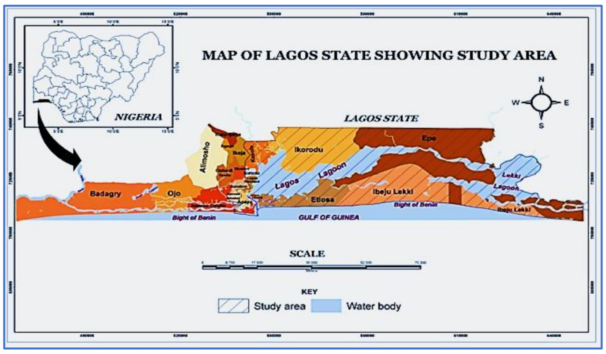

Figure 2: An Aerial photograph of Eti-Osa Local Government Area with water bodies around it.

Energy Demand Assessment

The urban settlement's load profile was obtained by gathering information on energy consumption from the residential parts only to determine the electricity demand profile using Excel software for four different categories of apartments: 28 Two-bedroom apartments, 12 Three-bedroom apartments, 52 Terrace apartments, and 48 Duplex apartments. The hourly load profile as shown in Figure 2 was estimated to understand the fluctuations in energy use to design a PV system that could meet both average and peak load requirements.

System Design and Sizing

The design and sizing of the PV system were based on the energy demand and solar resource assessment. The steps were as follows:

Solar Photovoltaic Sizing

The total load demand, energy lost in the system, lowest daily average peak-sun hours of a month in a year (solar irradiance), DC System voltage, rated module current and rated module voltage (which are obtained from the Canadian Solar datasheet) are required for the sizing and number of the photovoltaic modules needed. Table 1 shows the electrical and mechanical details of the Canadian Solar panel chosen for this study.

Table 1: Electrical and Mechanical details of Solar PV Module

Electrical Data	Mechanical Data
Nominal Max Power (P_{max}) = 315W	Make: Canadian Solar Model: CS6K- 300MS

Opt. Operating Voltage (V_{mp}) = 32.5V	Cell type: Monocrystalline
Opt. Operating Current (I_{mp}) = 9.24A	Cell arrangement: 60 (6 x 10)
Short circuit current (I_{sc}) = 9.83A	Dimension: 1650 x 992 x 35mm
Cell temperature = 25°C	
Ambient temperature = 20°C	

Thus, the Solar PV sizing can be calculated using the following equations (Owolabi, et al.,2019; Ali, et al.,2018; Egbon, et al.,2018).

iT_{wp} = Total wattage of the required panels, (W) = $\frac{P_p}{PGF}$ (1)

I_{DC} = Total current needed, (A) = $\frac{T_{wp}}{V_{DC}}$ (2)

N_p = Number of parallel modules = $\frac{I_{DC}}{I_r}$ (3)

N_s = Number of modules in series, = $\frac{V_{DC}}{V_r}$ (4)

N_m = Total Number of modules, = $N_p \times N_s$ (5)

where,

T_{LD} = Total load demand (Wh)

E_{lost} = Energy lost in the system,

PGF = Power Generation Factor (Owolabi *et al.,* 2019)

P_p = Energy required from PV modules,

V_{DC}= DC System voltage (V)

I_r = Rated module current (A)

V_r = Rated module voltage (V)

Battery Sizing

Of all the types of batteries, lead-acid batteries are simply because they are easily accessible, inexpensive, have a long lifespan, and integrate seamlessly with standalone solar power systems (Ali, *et al.,*2018). The Thunder Volt TJ185-250AGM 12V 250AH was used in this study, and its details are shown in Table 2.

Table 2: Details of Battery

Brand name: ThunderVolt
Model number: TJ185-250AGM
Volt Amp hour: 12V 250Ah
12V 250Ah @ 20hr Rate
Excellent cycle life:
CyclicUse:50%DOD-1200cycles - Cyclic Use: 80% DOD - 800 cycles
Industry Type No. TJ185
Weight (kg) 66.5
Nominal Voltage 12V
Length(mm): 38
Width(mm): 180
Height(mm): Total Height(mm): 426
Max Charge Current: 75A

The Battery sizing can be obtained by using equations (6) to (9) (Ali, *et al.,*2018; Al-Shamani, *et al.,*2015) where:

a Total Load Demand, (Wh) = T_{LD}

DC System voltage (V) = V_{DC}

Days of Autonomy = $\boldsymbol{D}_{aut}$

Factor to account for Efficiency = = $\boldsymbol{e}_{factor}$

Capacity of single battery, $(Ah)_{batt} = C_{batt}$

Voltage Rating of a single battery selected, (V) = V_r

Capacity of Battery bank (Ah)$_{bank}$ $= C_{bank} = \frac{T_{LD}}{V_{DC}} \times \boldsymbol{D}_{aut} \times \boldsymbol{e}_{factor}$ (6)

Then, to obtain the total number of batteries, the capacity of the battery bank is divided by the capacity of a single battery as seen in equation (1).

Total number of batteries, $N_{batteries} = \frac{C_{bank}}{C_{batt}}$ (7)

Number of batteries in series, $N_s = \frac{V_{DC}}{V_r}$ (8)

Number of batteries in parallel, $N_p = \frac{N_{batteries}}{N_s}$ (9)

Charge Controller Sizing

Using a suitable solar charge controller to control the battery charging process between the batteries and solar array will help address the overcharging and undercharging problems associated with batteries. Size requirements for solar charge controllers are determined by their voltage and current specifications. The mathematical formula for calculating the current rating of a charge controller for all the house categories is presented in equation (10).

Size of Charge Controllers in Amperes, $I_{ccs} = I_{sc} \times N_p \times S_f$ (10)

where, Short circuit current, (A) $= I_{sc}$

Number of parallel modules, $= N_p$

Safety factor $= S_f$

Charge Controller rating $= 100A$

Inverter Sizing

An adequate inverter output capacity is required in a stand-alone system to meet the energy demands of the peak load. As such its size should be 20–30% more than the total energy of the full operational load in order to guarantee safety. The inverter size can be computed using equation (11).

Inverter size, (W), $S_{inv} = T_{LD} \times S_f$ (11)

where,

Total load demand, (Wh) $= T_{LD}$

Safety factor, $= S_f$

Hours of usage = 24

Inverter rating $= I_{invr}$

4. Results

This section presents the results from the sizing of a photovoltaic (PV) system for an urban settlement located in a flood-prone area in Southwest Nigeria as shown in Table 3. The system was designed to meet the community's energy demands while considering the region's specific climatic conditions, including solar resource availability. The following discussion highlights the findings from the energy demand assessment, solar resource evaluation, system design and the environmental implications of the proposed PV system.

Table 3: Summary of the Total Daily Energy Consumption for the Four Categories of Apartment

Category of Apartment	Daily Power Consumption (Wh/day)	Number of Houses	Total Watts hour/day (kWh/day)
2-bedroom	3.1199	28	61.15
3-bedroom	4.8834	12	41.02
Terrace	7.8107	52	284.31
Duplex	11.7226	48	393.88

1. Energy Demand Results

The energy demand assessment for the urban settlement revealed a total daily energy requirement of 780.4 kWh for 140 apartments. The total daily energy consumption per category of apartments (2-Bedroom, 3-Bedroom, and Terrace) includes 61.15kWh/day, 41.02 kWh/day, and 284.31 kWh/day respectively. Peak consumption occurred in the evening (6 pm to 9 pm), which is typical for residential areas where the consumers are mostly at home from their daily activities as presented in Figure 3. The PV system was sized to not only meet current demand but to ensure long-term energy sustainability and also to minimize their dependence on the conventional grid, which is often affected by floods in such flood-prone areas.

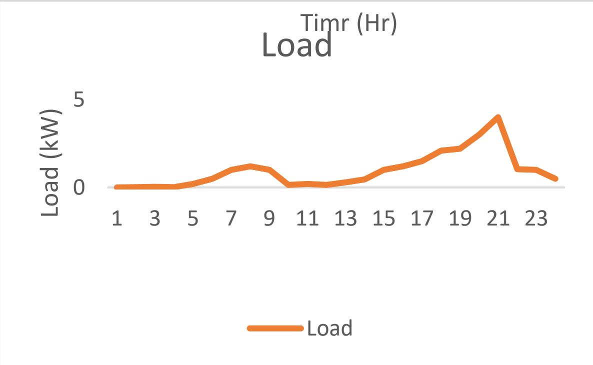

Figure 3: Hourly Load Profile of the Residential Estate

2. Solar Resource Assessment Results

The solar resource analysis showed that the selected location in Eti-Osa local government area in Southwest Nigeria experiences an annual average solar irradiation of 4.59 kWh/m²/day, with variations between the dry and wet seasons. During the dry season (November to April), solar radiation peaks at 5.06 kWh/m²/day, while during the rainy season (May to October), it sees lower solar irradiation, at 3.79 kWh/m²/day as seen in Figure 4. Even though these differences are substantial, the area can still generate solar energy. The average solar resource is sufficient to support a photovoltaic system designed to meet the urban community's energy demand. While solar irradiation is reduced during the rainy season, the integration of a battery storage system ensures that energy demand is met during periods of low solar generation. The system was designed to withstand these variations by utilizing stored energy from the battery to offset reduced solar generation during the rainy season. Figure 5 also presents the change in temperature for the selected location. An increase in temperature can be seen from January up till April which is indicative of availability of solar irradiation. A decline in temperature from the month of May to July points to rainy season. The decrease in temperature in August is suggestive of a short spell of moderate dryness which creates a platform for another rainy season from September to October. This later transcends into harmattan period also known as north-east monsoon from November to December.

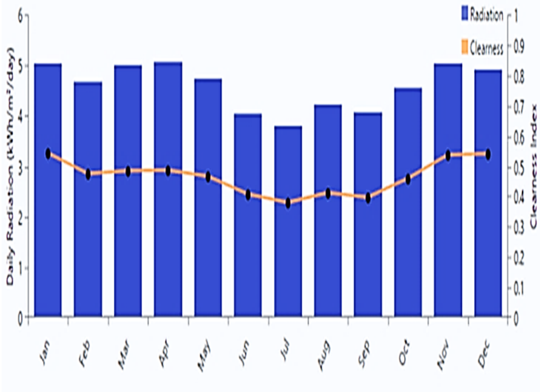

Figure 4: Monthly Annual Average Solar Global Horizontal Irradiation of the Residential Estate

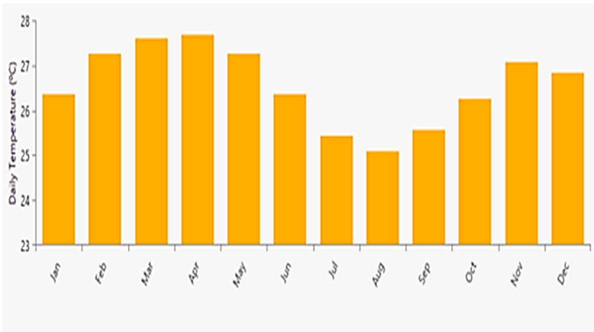

Figure 5: Monthly Annual Average Temperature of the Residential Estate

3. *System Sizing and Performance Results*

Based on the energy demand and solar resource availability, a 315W Canadian Solar PV module of CS6K=300MS model was selected. For each category of apartment type (2-bedroom, 3-bedroom, Terrace and Duplex), the number of photovoltaic panels needed are 3, 5, 7 and 11 respectively, while the storage system needed were 1.1 ,2

The storage system was designed to have a capacity of 10 kWh, allowing the community to draw on stored energy during the night and cloudy periods. This size of storage capacity ensures that the system would have autonomy for at least 24 hours without relying on grid power or supplemental sources. A 6 kW inverter was selected to accommodate peak load demands, and charge controllers were used to regulate the charging and discharging of the battery bank to maximize efficiency and battery life.

4. *Environmental Impact Results*

The environmental impact of the photovoltaic system was also evaluated using HOMER Pro software as presented in Figure 6, with a focus on its potential to reduce carbon emissions. The results obtained showed zero value, that there was no emission of carbon dioxide, carbon monoxide, sulphur dioxide, and nitrogen oxide, among other pollutants, into the environment and in return no consumer will be harmed. The contribution of renewable energy to the shift of a more sustainable energy future is highlighted by this decrease in carbon emissions. In addition to offering a cleaner energy source, the PV system complies with Nigeria's climate goals and international climate agreements by replacing fossil fuel-based power generation.

Quantity	Value	Unit
Carbon Dioxide	0	kg/y
Carbon Monoxide	0	kg/y
Unburned Hydrocarbons	0	kg/y
Particulate Matter	0	kg/y
Sulfur Dioxide	0	kg/y
Nitrogen Oxides	0	kg/y

Figure 6: HOMER Pro representation of the Environmental impact for the Residential location

5. Discussion

Every concerns as relating environmental effects will be taken care of if the proposed photovoltaic system is deployed for residents in the urban settlement of Southwest, Nigeria as indicated from the results. Not only will the environmental effects be catered for alone, the energy demands of the residents in this settlement will be satisfied too. Irrespective of either when there is enough sunlight or during flood events, to guarantee that the proposed system will function reliably, the system's design must comprise of a correct ratio of solar panels and battery storage for it to yield its maximum output. Its capacity to lower carbon emissions and aid in the fight against climate change further emphasizes the system's wider environmental advantages. Hence, for areas that are prone to flood and with an unreliable access to utility grid, it is suggestive from the result obtained that the solar energy can indeed sustain such areas by providing a sustainable energy without having to remain in the dark. Though the seasonal changes in solar irradiation were some challenges that were encountered, which could affect the efficiency during the rainy season. A strong battery storage system could be incorporated in order to fix this. Such that the possibility of hybrid systems that combine additional renewable energy sources to improve durability and dependence amid these scenarios may be reviewed in future studies.

Sizing of the photovoltaic system in this regard for the urban settlement in a flood-prone area situated in Southwest Nigeria illustrated how solar energy can be channeled to help meet the energy demands of dwellers in such areas. For urban settlements with similar challenges in Nigeria and across the Sub-Saharan Africa, this study can serve as a useful model by going through a thorough analysis to closely examine its energy demands, what renewable resources can be utilized and the photovoltaic system prerequisites for that specific location. In so doing, not only will the energy security be enhanced. the sustainable development will be supported as well as the effects of climate change will be allayed.

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