An impact of solar PV specifications on module peak power and number of modules: A case study of a five-bedroom residential duplex

Sogo Mayokun Abolarin\textsuperscript{1,3}, Manasseh Babale Shitta\textsuperscript{2}, Metuaghan Aghogho Emmanuel\textsuperscript{2}, Blessing Precious Nwosu\textsuperscript{2}, Michael Chucks Aninyem\textsuperscript{2} and Louis Lagrange\textsuperscript{1}

\textsuperscript{1}Department Engineering Sciences, University of The Free State, South Africa
\textsuperscript{2}National Centre for Energy Efficiency and Conservation, [Energy Commission of Nigeria], Faculty of Engineering, University of Lagos, Nigeria
\textsuperscript{3}E-mail: abolarinism@ufs.ac.za

Abstract. This paper presents a case study using an analysis of solar PV modules peak power to determine the optimum number of PV modules required to supply energy to certain typical household appliances. The approach could be used for selection of solar PV modules that produce a satisfactory energy yield to meet pre-determined energy needs. In the analysis, the maximum daily energy consumption values corresponding to the lighting and air-conditioning loads were determined through an energy audit conducted on a residential building unit in Lagos, Nigeria. The maximum daily energy consumption values of these appliances were programmed into a NCEEC e-EASZ VBA simulation tool to determine the solar PV array peak power and the number of modules required to produce the required solar energy yield. The methodology was validated with literature and HOMER Pro software. Eighteen different commercially available modules spanning a range of specifications including unit peak power varying from 280 to 400 W were investigated in order to select the most suitable panels for the provided conditions. The minimum required number of PV modules required to make up an array to produce the required yield was determined. The result indicates that when the unit peak power of the modules increases, the number of modules required to meet the daily energy demand reduces. The rating of solar PV modules between 280 - 400 W constituted a significant role in the process of analysing peak power as well as the quantity of solar PV modules required.

1. Introduction
The current trend of an increase in the consumption of fossil fuels (coal, oil, or gas) as primary sources of energy is contributing to the diminishing of natural energy reserves. The simultaneous increase in the release of greenhouse gases into the atmosphere contributes to global warming [1-4]. This calls for the consideration of viable alternatives including renewable and sustainable sources of energy such as solar, wind, biomass, tides, geothermal heat energy, etc. [5-9]. Generally, these renewable energy sources are either connected to the grid or off-grid using two-stage integrated topologies of direct current to alternating current and direct to direct current [10]. Amongst these alternative sources, solar energy is the most abundantly available worldwide. According to Wang, Liu, Wang, Zhu, Liu, Lin and Li [11], the growing use of solar PV systems is contributing to the fossil fuel crisis resolution and
drive the optimization of energy structures. Africa is generally known for its low access to energy but is endowed with an abundance of high solar irradiation with the potential to be utilized to meet its energy needs [12, 13]. Nigeria in particular receives high levels of solar radiation throughout the year. Efforts are thus being channeled towards unlocking this potential of available solar radiation. This could enable end-users of energy throughout the country to harness clean energy for productive activities and as such address the problems of shortage of power supply and greenhouse gas emissions.

The imbedded energy in solar radiation can be harnessed through either solar photovoltaic (PV) or thermal technologies of which the use has little direct destructive effects on the environment while it produces no carbon-dioxide emissions and requires relatively little or no maintenance [14].

Solar PV technology is gaining popularity as a sustainable alternative method to generate electricity. As a result, clean energy end-users, researchers and industrialists in several countries are showing an increased interest in solar PV designs and installations for residential, commercial and industrial buildings [15]. Solar PV technology is used to provide a clean and alternative energy source for energy use in buildings, particularly in residential buildings. Some of the prevalent energy uses include lighting, plug loads like television and refrigerators and air-conditioning units [12, 16].

Modules of similar specification do not produce the same yield with the least module quantities. A knowledge gap exists in this area which is to be rectified for people intending to use solar modules as an alternative source of energy. Morcillo-Herrera, Hernández-Sánchez and Flota-Bañuelos [17] used MATLAB in a study to determine the number of solar PV modules for 95% of the energy consumption of a waste treatment plant. Other studies used simulations through using HOMER Pro, PVSol, PVWatts, RETScreen etc., for solar PV sizing [18, 19]. To account for losses and solar intermittency Leonics [20] recommended a multiplier of 1.3 for determining the peak power.

Specifications for solar PV modules generally include unit peak power, maximum voltage, open circuit voltage, short circuit voltage, module efficiency, performance tolerance, working temperature, physical dimensions, etc. The unit peak power forms a significant specification input into the design as it represents a major determining factor of the array peak power and number of modules.

This study contributes to the body of knowledge on influence of unit peak power on the number of modules required to meet the maximum daily energy consumption of lighting and air-conditioning loads in a residential building. This contribution is achieved by comparing eighteen commercially available PV modules with different unit peak powers ranging from 280 W to 400 W and pseudonyms “A”-“R”.

2. Methodology

The daily energy consumption data of energy use for lighting and air-conditioning systems of a 5-bedroom residential duplex were obtained over a period. The energy use assessment methodology developed by Lagrange [21] as depicted in Figure 1 was used. This method comprises of a preliminary energy use assessment to inform the audit plan, the determination of correct metrics and the execution of the selected level of audit as specified by the American Society of Heating Refrigeration and Air-conditioning (ASHRAE) [22].

The preliminary audit in this case study consisted of obtaining consent from the owner and occupants and the initial collection of data. This informed the scope and extent of the audit plan and the relevant metrics identified for this study was energy consumption per day. An ASHRAE level 1 energy audit (walk-through energy survey) and ASHRAE level 2 (energy survey and analysis) with metering and monitoring collected data over a period of five days. Time stamped energy audit data were collected and recorded on the type, quantity, hours of use and capacity of the energy uses, and the resulting energy survey and analysis enabled the determination of the typical daily peak energy consumption of the appliances. The recorded data were stored in the NCEEC_e-EASZ VBA simulation tool for detailed analysis.

The energy audit data analysis was used to identify improvements in the energy design and appliance selection in the building unit [23]. The two energy uses, and their corresponding daily peak energy consumption are summarized in Table 1.
Figure 1. The Lagrange methodology to energy use assessments [21].

Table 1. Energy use and consumption in the residential building unit.

| Energy use             | Daily maximum energy consumption [kWh] |
|------------------------|----------------------------------------|
| Lighting               | 48.02                                  |
| Air-conditioning unit  | 213.73                                 |

The rating of the lighting varied from 10 W to 100 W input per fixture, while the rated input power of the air-conditioning units varied from 1160 W to 2100 W, varying with hours of use between 3 h/day up to 17 h/day. The time stamped hours of use per day were collected over a period of five days while other variables remained constant. The daily peak energy consumption for lighting was 48.02 kWh and for the air-conditioning 213.73 kWh.

The appliances’ maximum daily energy consumption aided the determination of the array peak power and the number of solar PV modules required to meet the demand. The eighteen PV modules were assigned with pseudonyms (“A” - “R”) and the manufacturers’ specification of each module was used in the data analysis.

Figure 2. GHI solar radiation of the location of the residential building (HOMER Pro).
The residential building’s longitude and latitude were specified in the HOMER Pro software (ver. 3.14.5) to generate the location’s daily solar global horizontal radiation profile available from National Renewable Laboratory Database and National Solar Radiation Database. This process enabled the determination of the average daily solar radiation of the location as this is generally known to be location or site dependent. From the HOMER Pro software, the location’s solar global horizontal radiation profile was generated from January to December. The location of the residential building has an average daily solar radiation of 4.8 kWh/m²/day (Figure 2).

3. Data analysis
The daily maximum energy consumption, $[EC]_{max}$ in kWh, was determined from the energy audit of the appliances used. Utilizing this daily energy consumption, the total size of solar PV, which is the solar PV array peak power, $P_{sp}$ in Watts, for each appliance was determined as a function of the daily energy consumption and solar sun hour, $S_{sh}$ (4.8 h).

$$P_{sp} = 1.3 \times \left( \frac{[EC]_{max}}{S_{sh}} \right) \times 1000$$  \hspace{1cm} (1)

To meet the daily energy demand and account for losses that could arise from the solar radiation intermittency, the solar PV peak power was increased by 30% [20].

The number of solar PV modules, $N_{sp}$ required was determined as a function of the solar PV peak power and the unit capacity of a selected solar module, $P_{up}$:

$$N_{sp} = \text{Even} \left( \text{Roundup} \left( \frac{P_{sp}}{P_{up}}, 0 \right) \right)$$  \hspace{1cm} (2)

The unit peak power of the solar PV modules used in this study varied from 280 - 400 W. The unit peak power of each module was captured in an excel spreadsheet tool called the National Centre for Energy Efficiency and Conservation Electronic Energy Audit and Solar sizing (NCEEC_e-EASZ) tool. The tool also serves as a database of over one hundred and fifty commercially available solar PV modules. This tool uses visual basic for Application (VBA) language and the energy audit data as input to analyse the data and generate results for this study.

4. Validation with literature
The method used in this study was validated with the correlations of Morcillo-Herrera, Hernández-Sánchez and Flota-Bañuelos [17], HOMER Pro Microgrid Analysis Tools (ver. x64 3.14.5) software and Leonics [20] using a 300 W solar PV module with 60 cell, dimension of 1.65 m by 0.992 m), efficiency of 18.33%, site derating factor of 32% and for the residential lighting energy use. The validation reveals approximately 52 modules with a Morcillo-Herrera, Hernández-Sánchez and Flota-Bañuelos [17] correlation, 35 modules using HOMER software and Leonics [20] (without accounting for losses) and 44 modules with accounting for losses and solar intermittency. This validation shows an excellent agreement with HOMER Pro software and Leonics [20]. This means that the methods used in this study, and results presented are within an acceptable accuracy level.

5. Results and discussion
To select the suitable solar PV module to achieve the needed energy yield while minimizing space, all eighteen pseudonym modules were considered. The specifications are summarized in Table 2. From Table 2 the number of solar PV modules required to meet the required lighting and air-conditioning (AC) loads varies with the unit peak power and dimension of the modules. This is further demonstrated in Figure 3 where it is shown that an increase in unit module peak power leads to reduction in the number of modules.
From Table 1 the building’s daily lighting energy requirement is 48.02 kWh with that of the air-conditioning is 213.73 kWh. The results from the different modules presented in Table 2 reveal that the number of modules required for lighting reduces as the unit peak power of each solar PV module increases. This is illustrated in Figure 4 as the number of required solar PV modules reduces from 48 to 34, for modules “A” to “R”. For the air-conditioning load the number of modules varied from 208 to 146 as the unit peak power increased, illustrated in Figure 5 and as the different modules were evaluated, shown in Figure 6. This reduction in the quantity of modules translates to significant reduction in total array area required to meet the same energy needs.

Figures 4 and 6 show that the pseudonyms and the pseudonym modules “A” - “R” have been individually evaluated to determine the peak power (Equation (1)) and the module quantity (Equation (2)) needed to produce the yield required to meet the maximum daily energy needs in the building under consideration.

**Table 2.** Specifications of the eighteen solar PV modules.

| Pseudonyms | A  | B  | C  | D  | E  | F  | G  | H  | I  |
|-------------|----|----|----|----|----|----|----|----|----|
| $P_{up}$ (W) | 280| 300| 320| 320| 340| 340| 340| 340| 340|
| $A_{up}$ (m²) | 1.64| 1.64| 1.63| 1.94| 1.79| 1.94| 2.01| 1.94| 1.94|
| $N_{sp}$ - Lighting | 48 | 44 | 42 | 42 | 40 | 40 | 40 | 40 | 40 |
| $N_{sp}$ - AC | 208| 194| 182| 182| 172| 172| 172| 172| 172|

| Pseudonyms | J  | K  | L  | M  | N  | O  | P  | Q  | R  |
|-------------|----|----|----|----|----|----|----|----|----|
| $P_{up}$ (W) | 360| 360| 360| 360| 360| 380| 380| 380| 400|
| $A_{up}$ (m²) | 1.64| 1.98| 1.98| 1.98| 1.64| 1.98| 1.97| 2.01| 2.01|
| $N_{sp}$ - Lighting | 38 | 38 | 38 | 38 | 36 | 36 | 36 | 34 | 34 |
| $N_{sp}$ - AC | 162| 162| 162| 162| 154| 154| 154| 146| 146|
From the list, only the module(s) capable of producing the yield with the least number of modules would be selected. Based on this, the selected suitable solar PV modules for these appliances are “Q” and “R”. This means that, in terms of the number of modules for “Q” and “R” 34 modules will be required for the lighting case as shown in Figure 4, while 146 modules would be required to produce the yield that meet the air conditioning load as indicated in Figure 6.

![Figure 4. Variation of solar PV modules quantity for the lighting requirements.](image)

![Figure 5. Number of solar PV modules against unit peak power for the air-conditioning.](image)
Figure 6. Variation of solar PV module quantity for the air-conditioning requirements.

From the specification and the results of this study, it is shown that the rating of solar PV modules between 280 W-400 W played a significant role in the process of analyzing peak power as well as the number of solar PV modules to be utilized.

6. Conclusions
To enable the energy users in this residential building to transition to clean energy and select suitable solar PV modules, an energy audit on the lighting and air-conditioning requirements provided the maximum daily energy consumption, which in turn was used to determine the number of modules required. The method used in this study was validated with literature and HOMER Pro software. Eighteen modules and their specifications were analyzed. The modules which produced energy that met the daily energy consumption loads at the least number of modules were selected. From the list of the solar PV modules considered, the result shows that only modules “Q” and “R” met the specifications for the set condition. This is because these modules produced minimum quantities required to meet the daily energy requirements for the lighting and air-conditioning load needs. Each of the modules “Q” and “R” could generate higher energy quantities than the daily energy requirement. The approach used in this study can be applied to help users select the perfect solar PV module as a lower number of modules was required in the case of “Q” and “R” to meet the same energy demand given for an optimized solar PV sizing.

Acknowledgement
The authors appreciate the University of The Free State for the financial support provided to attend this conference and publication.

References
[1] Mahachi T 2016 Energy yield analysis and evaluation of solar irradiance models for a utility scale solar PV plant in South Africa. In: Electrical and Electronics Department, Faculty of Engineering, (Stellenbosch, South Africa: Stellenbosch University)
[2] Abolarin S M, Gbadegesin A O, Shitta M B, Yussuff A, Eguma C A, Ehwerhemuepha L and Adegbemro O 2013 A collective approach to reducing carbon dioxide emission: A case study of four University of Lagos Halls of residence Energy and Buildings 61 318-22
[3] Xu Y, Guo X, Yu Q, Huang Y, Wang J, Sun H, Ma X, Guan J, Li W, Song Z and Jia G 2020
Experimental and numerical investigation of combustion system improvement on 600MW bituminous coal boiler for burning lignite coal IOP Conference Series: Earth and Environmental Science 467 012042

[4] Chen Y, Zheng L, Huang J, Zou Z and Li C 2020 Prediction of gas emission based on grey-generalized regression neural network IOP Conference Series: Earth and Environmental Science 467 012056

[5] Adewuyi O B, Kiptoo M K, Afolayan A F, Amara T, Alawode O I and Senjyu T 2020 Challenges and prospects of Nigeria’s sustainable energy transition with lessons from other countries’ experiences Energy Reports 6 993-1009

[6] Wang H, Xin S, Zhang P, Hu C, Lu X, Lei X, Chen J, Kuang W, Wu W, Gu C and Xie G 2020 Study on the actual operation characteristics of fluidized bed heat exchanger in a supercritical CFB boiler IOP Conference Series: Earth and Environmental Science 467 012012

[7] Ji Y, Li Y and Li H 2020 Study of key structure parameters on productivity of the ring-die biomass granulator IOP Conference Series: Earth and Environmental Science 467 012054

[8] Ojolo S J, Abolarin S M and Adegbenro O 2012 Development of a laboratory scale updraft gasifier International Journal of Manufacturing Systems 2 21-42

[9] Ojolo S, Orisaleye J, Ismail S and Abolarin S M 2012 Technical potential of biomass energy in Nigeria Ife Journal of Technology 21 60-5

[10] Gao G, Zeng J, Han J and Lei X 2020 Design of backstepping controller for T-type network inverter IOP Conference Series: Earth and Environmental Science 467 012030

[11] Wang X, Liu F, Wang Y, Zhu M, Liu Y, Lin Z and Li H 2020 Optimized dispatching based on wind-photovoltaic-hydropower-thermal-bundled strategy IOP Conference Series: Earth and Environmental Science 467 012038

[12] Chisale S W and Mangani P 2021 Energy audit and feasibility of solar PV energy system: Case of a commercial building Journal of Energy 2021 5544664

[13] Kaya M 2020 Evaluation of the Existing Solar Energy and Rainwater Potential in the Total Roof Area of Buildings: Izmit District Example Advances in Materials Science and Engineering 2020 8167402

[14] Abdul-Wahab S, Charabi Y, Al-Mahruqi A M, Osman I and Osman S 2019 Selection of the best solar photovoltaic (PV) for Oman Solar Energy 188 1156-68

[15] Usman Z, Tah J, Abanda H and Nche C 2020 A critical appraisal of PV-systems’ performance Buildings 10 192

[16] Abolarin S M, Gbadegesin A O, Shitta B M and Adegbenro O 2011 Energy (lighting) audit of four University of Lagos halls of residence Journal of Engineering Research 16 1-10

[17] Morcillo-Herrera C, Hernández-Sánchez F and Flota-Bañuelos M 2015 Method to calculate the electricity generated by a photovoltaic cell, based on its mathematical model simulations in MATLAB International Journal of Photoenergy Volume 2015 1-12

[18] Khalil L, Liaquat Bhatti K, Arslan Iqbal Awan M, Riaz M, Khalil K and Alwaz N 2021 Optimization and designing of hybrid power system using HOMER pro Materials Today: Proceedings 47 S110-S5

[19] Deshmukh M K and Singh A B 2019 Modeling of energy performance of stand-alone SPV system using HOMER Pro Energy Procedia 156 90-4

[20] Leonics 2019 How to design solar PV system. Leonics)

[21] Lagrange L F 2016 Energy use assessment methodology, fundamentals of energy management training (FEMT) course notes. ed Em Section 6

[22] ANSI, ASHRAE and ACCA 2018 Standard for commercial building energy audits. (Atlanta: ASHRAE) pp 1-7

[23] Sendrayaperumal A, Mahapatra S, Parida S S, Surana K, Balamurugan P, Natrayan L and Paramasivam P 2021 Energy auditing for efficient planning and implementation in commercial and residential buildings Advances in Civil Engineering 2021 1908568