Nigerian Research Journal of Engineering and Environmental Sciences 4(2) 2019 pp. 972-982

Nigerian Research Journal of Engineering and Environmental Sciences
Journal homepage: www.rjees.com

Original Research Article

Optimal Design of a Stand-Alone Photovoltaic System

Agbonaye, O. and *Odiase, F.O.
Department of Electrical and Electronics Engineering, Faculty of Engineering, University of Benin, PMB 1154, Benin City, Nigeria.
*osasere.odiase@uniben.edu

ARTICLE INFORMATION

Article history:
Received 29 May, 2018
Revised 09 Dec, 2019
Accepted 11 Dec, 2019
Available online 30 Dec, 2019

Keywords:
Photovoltaic systems
Standalone
Renewable energy
Homer
Load management

ABSTRACT

This study focused on finding an optimal design method for sizing a stand-alone photovoltaic mini-grid to provide sustainable and reliable power to a house. Optimal size of the photovoltaic array, battery, and inverter was calculated using appropriate equations. Simulations were carried out using the Homer software to verify the optimal design for a residential house in Guru Karaftayi village in Kazaure Local Government Area of Jigawa state, Nigeria. After optimal design and simulations, the battery size with 12.96 kWh and a Photovoltaic Array size of 2.2 kW was chosen as optimal. Simulation results showed it could supply power for 10 years with annual capacity shortage of 171.86 kWh/yr and 502 outage hours in a year. The Net present cost of the system was $8,913. The project clearly proves that a standalone photovoltaic mini-grid can be implemented reliably and economically with this optimal design method.

1. INTRODUCTION

The possibility of converting solar radiation into electrical energy has made it suitable in many applications. Solar radiation can be converted into electricity using a photovoltaic (PV) system. Solar electricity may be used for power supply to remote villages and locations not connected to the national grid. It may also be used to generate power for feeding into the national grid. Other common areas of application of solar electricity include low and medium power application such as water pumping, village electrification, rural clinic and school power supply, vaccine refrigeration, traffic lighting and lighting of road (Sambo, 2010). In Nigeria most of the photovoltaic system employed to provide electricity service to rural communities for street lighting, water pumping, primary health centres, refrigerators and TV viewing centres are government sponsored project (Ogedengbe and Adamolekun, 2017).

A standalone PV system is one in which the PV panel is the only source of power and is intermittent because the sun does not shine throughout the day and the load demand varies through the day (Zhou, et al., 2008). For example, a residential house would have higher load demand in the morning and evening when most activities are taking place and less demand in the afternoon when the occupants have gone to work. In the opposite, the PV array installed in the home would experience less solar radiations in the morning and evening and experience more in the afternoon when radiation is highest. There is also seasonal fluctuations and mismatch between the load and the solar radiation during the year. Some months are characterized by high rainfall, smaller solar window; this surely reduces the solar radiation received by the PV Array. A battery is needed to take care of this mismatch. The work of the battery is to store excess energy generated by the PV array during the solar window and supply that energy when there is load demand but no or insufficient solar radiation.

This work focuses on an optimal design method for sizing photovoltaic system for rural residential house.

2. METHODOLOGY

The load demand was estimated by itemizing all the electrical appliances in the home, their power rating, and usage hours. Then the average daily energy demand in watt-hours was calculated. The average daily demand was used for sizing the PV array and battery (Munro, 2010). The number of hours we want the battery to cater for the load (optimal hour of autonomy) was hypothesized using the solar window and confirmed by simulation using Homer software. Different sizes of PV array were also experimented with by simulation to confirm calculation for the optimal PV array size.

2.1. Load Profile Calculation

Figure 1 is a sketch of the sample home showing the connected electrical load. To design a mini-grid that can effectively cater for these loads, the average daily load demand has to be calculated (NZER, 2010).

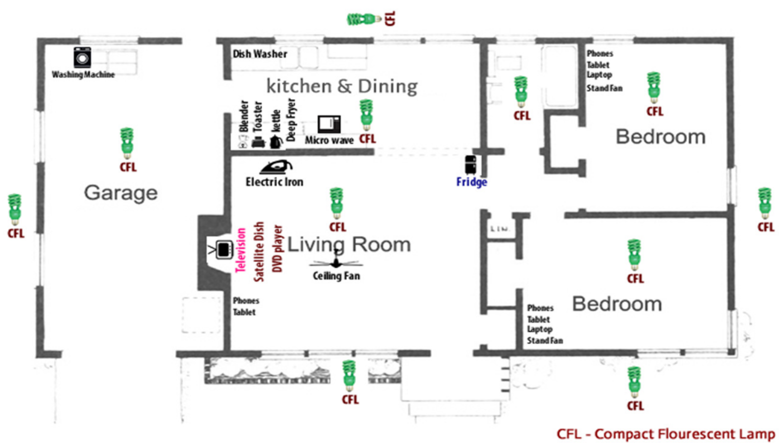

Figure: 1: Sketch of the sample home showing the connected electrical load

2.2. PV Array Design and Optimization

The area of the PV panel that can extract the required power to meet the load demand for any location with a global horizontal irradiance was calculated from Equation (1) (Bataineh et al., 2012).

$$PV\ area\ required\ = \frac{E\text{lday}}{H\text{in}\ x\ \eta\text{pv}\ x\ \eta\text{loss}\ x\ K\text{derating}} \quad (1)$$

Where H_{in} is the global horizontal irradiance (kWh/m^2/day), η_{pv} is Efficiency of PV module, Kderating is a factor that accounts for losses due to temperature effect, dirt, PV output tolerance, shading, and wire. ηloss is the product of the battery and inverter efficiency.

$$\eta_{loss} = \eta bat \text{ x } \eta inv \quad (2)$$

$$K_{derating} = Ktemp x \; Kprod \; x \; Kshade \; x \; Kdirt \; x \; \eta wire \quad (3)$$

Where ηbat is battery efficiency and η_{inv} is inverter efficiency, Ktemp is the temperature loss factor, Kprod is PV module output power tolerance factor, Kshade is factor to account for array shading, Kdirt is the PV module dirt derating factor, ηwire is efficiency to account for wire loss (Openelectrical, 2015).

The PV module temperature loss factor (Ktemp) is dependent on the module installed and the average ambient maximum temperature for the location. Temperature loss factor was calculated from Equation (4).

$$Ktemp = 1 + (\gamma \times (T_{cell.eff} - T_{stc})) \quad (4)$$

Where γ is power temperature coefficient per °C, $T_{cell.eff}$ is the Nominal Operating Cell Temperature (NOCT) in ° C, T_{stc} is the cell temperature at standard test conditions, in ° C (CEC, 2009).

The required PV output power generated from the PV area was calculated from Equation (5) (Bataineh et al., 2012).

$$PV_{output} = PV \; area \; required \; x \; PSI \; x \; \eta pv \quad (5)$$

Where PV_{output} is the power output of the PV array from the PV area, PSI is the maximum radiation intensity. PV_{output} is 1000 W/m^2 at standard test condition while η_{pv} is the efficiency of PV module.

The number of modules that would provide this PV array output was calculated from Equation (6) (Guda and Aliyu, 2015).

$$N_{modules} = \frac{PVoutput}{Pmpeak} \quad (6)$$

Where $N_{modules}$ is the number of modules to meet this required output, P_{mpeak} is the peak power of the choose module.

The modules are connected in series and parallel to form the PV Array. The number of modules in series (N_{ms}) was determined by dividing the voltage the system is designed for by the nominal voltage of the module at standard test condition, (Equation 7) (Guda and Aliyu, 2015).

$$N_{ms} = \frac{V system}{V module} \quad (7)$$

The number of modules in parallel (N_{mp}) was obtained by dividing total array output by a single module output, as shown in Equation 8 (Guda and Aliyu, 2015).

$$N_{mp} = \frac{P pv}{N ms \; x \; P module} \quad (8)$$

For the case study (Karaftayi in Jigawa state), the average solar global irradiance is 6.04 kWh/m^2/day (Nasa.gov, 2017). Average load demand for the residential house is 7.425 kWh. The GS-STAR-100 W PV module was chosen primarily because of its (unit capacity of 100 W) which enabled simulation to be perform easily with increment of 100 W sizes using Homer software. However, the choice of PV module should be based mainly on efficiency, cost, and availability. Battery efficiency, ηbat ("both VISION CP6100D and Rolls 12CS11P batteries) is 0.8; Inverter efficiency, ηinv ("MS PWRINV10KW " 12V inverter) is 0.90. From data sheet for PV module GS-STAR-100W, nominal operating cell temperature is 46^o C, temperature coefficient of P_{max} is -0.45 %/°C, T_{STC} is 25^o C, PV module max output power tolerance is 0% to +6% hence chosen PV module max output power tolerance factor, Kprod as 1.0, PV module shading derating factor, K"shade " as 0.98,PV module dirt derating factor,K"dirt " as 0.95 and Wire loss (GrapeSolar.com, 2015).

2.3. Battery Design and Optimization

A battery has limit to how much it can discharge every cycle without being damaged and how much energy it can give out throughout its lifetime. The battery size was effectively optimized by:

1) Finding the optimal depth of discharge for the battery lifetime

2) Finding the hours of autonomy that would give the optimal battery size (low cost and low outage hours).

2.3.1. Depth of discharge

In finding the optimal depth of discharge it was assumed that a battery is discharged once every day awaiting the next solar window for charging. Hence, the optimal number of cycles to failure would be the same as the desired battery life in days, this optimal number of cycles to failure is used to determine the optimal depth of discharge. For ROLLS 12CS11P DOD for 10 years lifetime (3650 cycles) is 0.4.

$$\text{Optimal depth of discharge} = \text{DOD at battery lifetime in days (cycles)} \quad (9)$$

2.3.2. Optimal battery size

The size of battery is mainly determined by the number of hours you want the battery to last for (hours of autonomy). The battery can only be allowed to discharge up to its chosen depth of discharge in order to reach its required lifetime. Hence, the size of battery chosen should sufficiently cater for the load demand for the required hours of autonomy. The optimal battery size, B_{size} was calculated from Equation 10.

$$B_{size} = \frac{\left(\sum_{t=0}^{t=H_{aut}} \text{El dt}\right)}{\text{DOD x } \eta\text{out}} \quad (10)$$

Where $E_{l\,dt}$ is the load demand at t hour, H_{aut} is the battery hours of Autonomy, $\sum_{t=0}^{t=H_{aut}}$ El dt is an expression used to show the load demand up to H_{aut} hours of autonomy, ηout is the battery output efficiency.

To reduce the complexity in calculating the average load demand up to the required hours of autonomy, the average hourly load demand can be used.

$$E\text{lhr} = \frac{E\text{lday}}{24} \quad (11)$$

Where E_{lhr} is the average hourly load demand and Elday is the average daily load demand

Hence, replacing ($\sum_{t=0}^{t=\text{Haut}}$ El dt) by (Elhr x Haut) in Equation (10) yields:

$$Bsize = \frac{(E\text{lhr}\ x\ H\text{aut})}{\text{DOD x }\eta\text{out}} \quad (12)$$

2.3.3. Total number of batteries

The total number of batteries required was obtained from Equation 13 (NABCEP, 2015).

$$\text{Total Number of batteries} = \frac{B\text{size}}{\text{Bsingle}} \quad (13)$$

Where B_{size} is the optimal battery size and B_{single} is the capacity of a single battery

$$\text{Number of batteries in series} = \frac{System\ Voltage}{battery\ voltage} \quad (14)$$

$$\text{Number of batteries in parallel} = \frac{Total\ Number\ of\ batteries}{Number\ of\ batteries\ in\ series} \quad (15)$$

2.3.4. Optimal Hour of Autonomy

The size of battery required majorly depends on the hours of autonomy to be designed for. The hour of autonomy is the number of hours the battery is able to cater for the load demand without recharging. A hypothesis for finding the optimal hour of autonomy is to use the number of hours in the solar window (hours of sunshine in the day). Karaftayi has a fairly constant solar window of 11 hours throughout the year, therefore 13 hours (24-11 hours) of autonomy was chosen. The optimal ROLLS 12CS11P DOD for 10 years lifetime (3650 cycles) is 0.4 and from Equation (12) battery, size is 12768.06 Wh. Using the ROLLS 12CS11P battery that has capacity of 4320 Wh per battery (Bataineh, et al., 2014). The total number of batteries required to meet the 12768.06 Wh for 13 hours autonomy is 2.96 (approximately 3 batteries). Three batteries will give a total capacity of 12960 Wh.

2.4. Inverter Design

The Inverter should be capable of handling the load demand if all appliances were to draw power simultaneously. It should also be able to take high starting current and normal surge from large loads. A safe method to estimate the maximum amount of surge the ac load can generate would be to multiply the AC load by 3. A safety factor of 1.25 can also be used to allow for rare high surge (Chris, 2015). The inverters voltage has to be matched with that of the battery bank. The power rating of the inverter, P_{inv} was calculated from Equation 16.

$$P_{inv} = (P_{rs} + 3P_{lsc}) \text{ x } 1.25 \quad (16)$$

Where P_{rs} is power of low surge appliances running simultaneously and P_{lsc} is power of large surge current appliances (Ishaq et al., 2015). For the case study, the likely appliances to surge are the refrigerator and the washing machine.

2.5. Cable Design

To ensure a good performance and a reliable system, the cables have to be properly sized. The current passing through the cable has to be determined, as well as the cable size that would result in minimal voltage drop. In both AC and DC wiring for standalone PV system the maximum voltage drop should not exceed 3 % (Sundog Energy, 2006). The length of cable should allow for ease of installation. There should also be some added length to allow for maintenance. There are three main cables in the PV system: the cable connecting the PV Array to the battery bank, the cable connecting the battery bank to the inverter, and the one connecting the inverter to the load.

2.5.1. Cable between PV array and battery bank

Firstly, the current produced from the module entering the battery bank was calculated from Equation (17) (Ishaq et al., 2015).

$$I_{rated} = N_{mp} \times I_{sc} \times F_{safety} \quad (17)$$

Where I_{rated} is the current from the PV module, N_{mp} is the number of modules in parallel

I_{sc} is the Short circuit current of the PV module, F_{safety} is Safety factor (usually taken as 1.25) to give the cable some lag in case of rare high currents (Ishaq et al., 2015).

The cable area was calculated from Equation (18).

$$A = \frac{\rho l I}{V\text{d}} \times 2 \quad (18)$$

Where ρ is the resistivity of copper cable (1.724 x $10^{-}8\Omega$m), l is the length of copper cable, I is the current passing through the cable, V_d is the maximum allowable voltage drop.

2.5.2. Cable between battery bank and inverter

The current from the battery bank was calculated from Equation (19). (Ishaq et al., 2015)

$$I_{max} = \frac{\text{Pinverter}}{\eta\text{inv} \times \text{Vsystem}} \quad (19)$$

Where I_{max} is the maximum current drawn from battery bank; $P_{inverter}$ is the inverter power rating and V_{system} is the Voltage of the battery bank

2.5.3. Cable between inverter and load

The current from the inverter drawn from the load was calculated from Equation (20) (Ishaq et al., 2015).

$$I_{phase} = \frac{\text{Pinverter}}{\text{Voutput} \times \sqrt{3}} \quad (20)$$

Where I_{phase} is the Phase current flowing to the load, $P_{inverter}$is the inverter power rating and V_{output} is the output phase voltage.

2.6. Economics

For every PV system design, it is necessary to do an economic analysis to determine how much money would be incurred in installing, operating, and maintaining the system. The salvage value for each component at the end of the project period is calculated from Equation (21) (Anayochukwu, 2013).

$$S = C_{\text{rep}} \left(R_{\text{rem}}/R_{\text{comp}}\right) \quad (21)$$

Where S is the Salvage value, C_{rep} is the Replacement cost of the component; R_{rem} and R_{comp} are the remaining life of the component, and the lifetime of the component respectively.

The net present cost (NPC) is used to represent the lifecycle cost of the system. The total annualized cost of the system includes capital cost of each components, installation cost, operation, maintenance, fuel cost, and penalty for pollutant emission. The total net present cost can be gotten from Equation (22) (Anayochukwu, 2013).

$$NPC = \frac{C_{ann,tot}}{CRF(\mathrm{I}, R_{proj})} \tag{22}$$

Where $C_{ann,tot}$ is the total annualized cost, I is the annual real interest rate (the discount rate), R_{proj} is the project lifetime; CRF is the capital recovery factor

The capital recovery factor is calculated from Equation (23) (Anayochukwu, 2013).

$$CRF(I, N) = \frac{i(I+i)N}{(I+i)N-1} \tag{23}$$

Where I is the Annual real interest rate, N is the Number of years.

The levelized cost of energy (COE) is the average cost per kilowatt-hour of electricity produced by the system. It is calculated from Equation (24) (Lambert et al., 2015).

$$COE = \frac{C_{ann,tot}}{E_{prim} + E_{def}} \tag{24}$$

Where $C_{ann,tot}$ is the Total annualized cost, E_{prim} and E_{def} are the total amounts of yearly primary and deferrable load, respectively.

Both the levelized cost of energy and the total NPC are convenient metrics used to compare the costs of different systems. An optimal design should have low COE and NPC.

3. RESULTS AND DISCUSSION

The calculated optimal design sizes were used for simulation using the Homer Software for a typical year. Result shows that the total number of outage hours in a year is 502, and the unmet load demand (capacity shortage) is 171.86 kWh/yr. Figure 2 shows the average capacity shortage for each month of the year, with July, August and September months mostly affected. Figure 4 shows the capacity shortage hourly profile for the 12 months of the year. Most of the capacity shortage happens in the morning between 5:00 am to 7:00 am, the maximum is 300 W shortage in August. Figure 5 shows cost summary by components. The battery takes a larger share of the cost. The total net present cost of the system is $8913. Figure 5 shows the number of outage hours for 1—60 hours of Autonomy. From the graph, most optimal number of hours of autonomy is 13. Figure 6 shows outage Hours Verses PV Array Size. From the graph, the most optimal PV Array size is 2.2 kW, the optimal PV size agrees with the theoretical result of 2.2 kW PV array size calculated using Equation 5. This shows that a cost effective and high performance standalone PV system can be designed using the method explained in this work. Figure 2 shows the average capacity shortage for each month of the year. July, August and September are the months that are mostly affected. The reliability of the system is mainly dependent on solar radiation. The capacity shortage hourly profile also shows that most of the capacity shortage happens in the morning between 5:00 am to 7:00 am. The maximum is 300 W shortage in Figure 2.

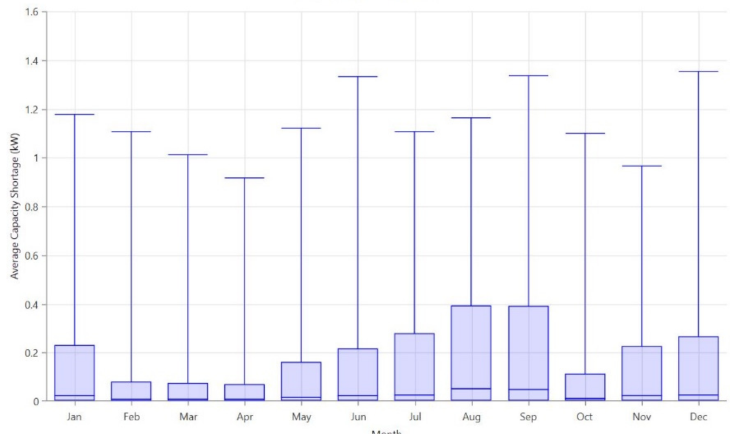

Figure 2: Capacity shortage monthly profile for the year

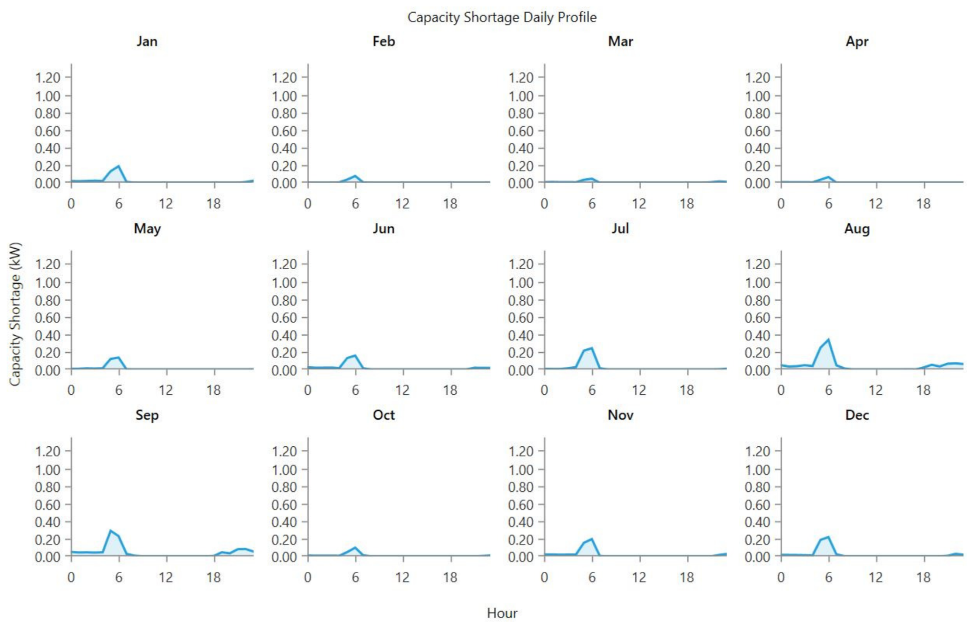

Figure 3: Capacity shortage hourly profile for 12 months of the year

3.1. Cost of the Optimal Design for Karaftayi

Table 1 shows a summary of the design. It shows the sizes of each system component, the model chosen and the price. Figure 4 shows a summary of the cost of the system components with the battery taking a larger share of the cost. The cost was calculated for a 10-year period. The PV array have a lifetime of 15 years; hence it has a salvage value of $1378 after the 10-year project period. The total net present cost of the system is $8913. Simulations carried out to find out / verify the hours of autonomy that would give the optimal battery size. This was done using the homer software to simulating the load, solar radiation, PV array output of 2.2 kW with different battery sizes for 1- 60 hours of autonomy. Figure 5 shows the number of outage hours for 1 – 60 hours of autonomy. From the graph, most optimal number of hours of autonomy is 13. Increasing the battery autonomy any further would cost so much for just little improvement in outage hours.

O. Agbonaye and F.O. Odiase / Nigerian Research Journal of Engineering and Environmental Sciences
4(2) 2019 pp. 972-982

Table 1: Summary of project design

Component	Description	Model	Total Capital Cost (dollars)
PV array	PV array capacity 2.2 kW Total no of modules 22	GS-STAR-100W	$4070 for 22 modules *(Grapesolar.com, 2015)*
Battery bank	Capacity of battery bank (13 hrs Autonomy) 12960 Wh	ROLLS 12CS11P	$4500 for 3 batteries *(Rollsbattery.com, 2015*
Inverter	Capacity of inverter 10 kW (20 kW surge)	AIMS PWRINV 10 kW 12V	$1100 *(Bataineh, et al., 2012)*
	Total capital cost		$9670

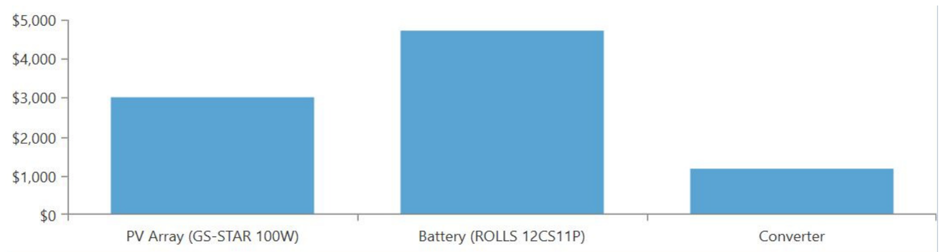

Figure 4: Cost Summary by component

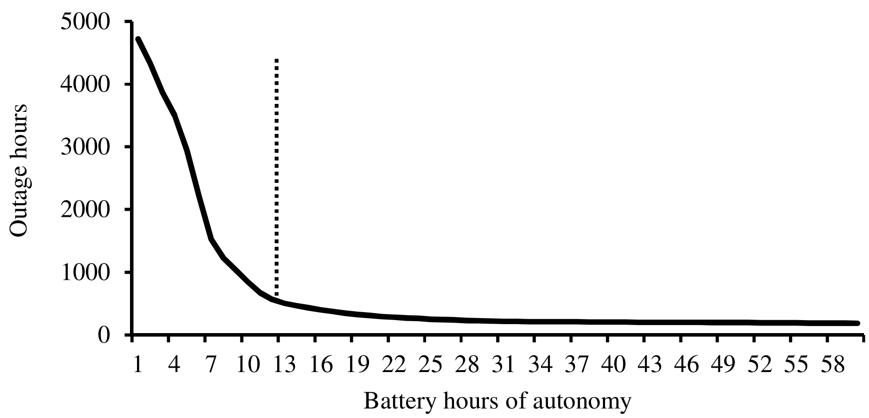

Figure 5: Outage hours versus hours of autonomy

Another set of simulations was done to find the optimal PV Array size. The PV array output was increased in steps of 100 W from 0 kW up to 5 kW using battery size of 12960 Wh to find the increase in systems performance and find the optimal value. The number of outage hours versus the PV Array sizes is shown in the Figure 6. From the graph, the most optimal PV Array size is 2.2 kW. Increasing the PV Array size any further would cost so much for just little improvement in outage hours.

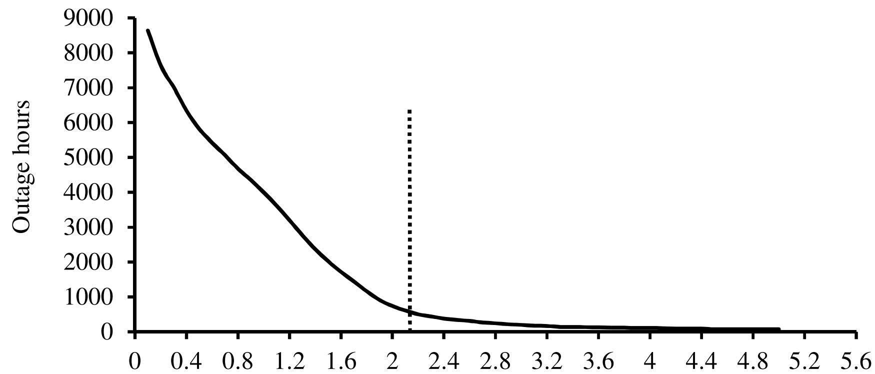

Figure 6: Outage hours versus PV array size

4. CONCLUSION

The project is carried out to find an optimal design method for an isolated PV system. A modern residential house with solar electricity in Karaftayi Village was used as a case study to verify the proposed optimization method. After optimal design and simulations, the battery size with 12.96 kWh was chosen while a PV size of 2.2 kW was chosen as optimal. It would be able to supply power for 10 years with annual capacity shortage of 171.86 kWh/yr and 502 outage hours in a year. The net present cost of the system is $8,913. To confirm the optimal design and hypothesis, sets of simulations were done using various combination of battery and PV sizes and plotting them to find the optimal size.

5. CONFLICT OF INTEREST

There is no conflict of interest associated with this work.

REFERENCES

Anayochukwu, A. (2013). Optimal Energy System for Single Household in Nigeria. *International Journal of Energy Optimization and Engineering*, 2(3), pp. 16-41.

Bataineh, A., Alqudah, A. and Athamneh, A. (2014). Optimal Design of Hybrid Power Generation System to Ensure Reliable Power Supply to the Health Center at Umm Jamal, Mafraq, Jordan. *Energy and Environment Research*, 4(3), pp. 134-139

Bataineh, K. and Dalalah, D. (2012). Optimal Configuration for Design of Stand-Alone PV System. *Smart Grid and Renewable Energy*, 03(02), pp. 139-147.

Chris, N. (2015). *Green Power at Edge Technology: honda, LPG, solar and wind*[online] Edge4renewable-energy.co.uk. Available at: http://www.edge4renewable-energy.co.uk/battery-banks.htm [Accessed 21 Aug. 2015].

Clean Energy Council (CEC) (2009). Grid connected PV Systems Design Guidelines for Accredited Designers. Issue 3 July, updated November, 2009.

Grapesolar.com. (2015). *SPECS - 100W POLY GS-Star-100W*. [online]. Available at: http://www.grapesolar.com/specs-100w-poly-gs-star-100w.html [Accessed 21 Aug. 2015].

Guda, H. and Aliyu, U. (2015). *Design of a Stand-Alone Photovoltaic System for a Residence in Bauchi. International Journal of Engineering and Technology*, 5(1), pp. 134-141

Ishaq,M., Ibrahim, H.,and Abubakar, H. (2015). *Design of an Off Grid Photovoltaic System: A Case Study of Government Technical College, Wudil, Kano State. International journal of scientific & technology research*, 3(12), pp. 123-132

Lambert, T., Gilman, P. and Lilienthal, P. (2015). *Micropower System Modeling with Homer*. Mistaya Engineering Inc., National Renewable Energy Laboratory.

Munro, K. (2010). *Designing a Stand-Alone PV System.* [online] Available at: http://www.homepower.com/articles/solar-electricity/design-installation/designing-stand-alone-pv-system?v=print [Accessed 21 Aug. 2015].

NABCEP (2015). *PV Installation Professional Resource Guide 2013. (2013)*. 1st ed. [ebook] Available at: http://www.nabcep.org/wp-content/uploads/2013/08/NABCEP-PV-Guide-7-16-13-W.pdf [Accessed 21 Aug. 2015].

Nasa.gov, (2017). NASA Surface Meteorology and Solar Energy: Daily Average Data", 2017 (online) Available http://eosweb.larc.nasa.gov/cgibin/sse/daily.cgi?email=skip@larc.nasa.gov (Accessed: 27-Aug-2017).

New Zealand Electricity Regulations, (NZER) (2010). *AS-NZS 4509-2 Stand-alone power systems - Part 2: System design*. (SR 2010/36)].

Ogedengbe, T.I. and Adamolekun, T.M. (2017). Issues in Solar Energy Technological Development in Nigeria. Proceedings of the 2017 Annual Conference of the school of Engineering and Engineering Technology (SEET). The Federal University of Technology, Akure, Nigeria. THEME: Innovative and Adaptive Technology for National Development.

Openelectrical (2015). *Battery Sizing - Open Electrical*. [online] Available at: http://www.openelectrical.org/wiki/index.php?title=Battery_Sizing [Accessed Aug. 2015].

Rollsbattery (2015). *Cycle Life vs. Depth of Discharge - 5000 Series: Technical Support Desk*. [online] Available at: http://support.rollsbattery.com/support/solutions/articles/8136-cycle-life-vs-depth-of-discharge-5000-series [Accessed 21 Aug. 2015].

Sambo, A.S. (2010). Renewable Energy Development in Nigeria. Paper presented at the meeting of the world future council/strategy workshop on Renewal Energy, Accra Ghana.

Sundog Energy (2006). Photovoltaics in Buildings Guide to the installation of PV systems. (2006). 2nd ed.

Zhou, K., Ferreira, J.A. and Hann, S.W.H. (2008). Optimal energy management strategy and system sizing method for stand-alone photovoltaic-hydrogen systems. *International Journal of Hydrogen Energy*, 33(2), pp. 477-489.