COMPARATIVE ANALYSIS OF SOLAR STREET LIGHTING SYSTEMS FOR SIX SELECTED LOCATIONS IN NIGERIA

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ABSTRACT

There is a desperate need for high-quality, affordable, and reliable lighting systems at sites where the electricity grid is either non-existent or unstable for applications such as security lighting. Many systems installed in Nigeria are failing due to poor design or wrong sizing of the components. This paper gives a detailed design and analysis of Stand-alone Solar Street Lighting Systems taking six selected locations in Nigeria as cases of the study for comparison. The variations of solar radiation and night lengths were considered. The monthly average solar radiation data were based on 22 years of monthly average insolation figures obtained from the National Aeronautics Space Administration (NASA). A single LED lamp rated 12V, 40W DC operating from dusk to dawn was used for the design. The results show that the length of nights varies seasonally with maximum values in December and minimum values in June for all the locations with places closest to the equator having the least variation. Components requirement indicates that a piece of 12V, 100Ah battery, and a piece of 12V, 20A charge controller will suffice for all the locations. The difference is based on solar array requirement in which the results show that 2 pieces of 120Wp solar panel connected in parallel will be adequate for PortHarcourt, and Benin-City; 2 pieces of 100Wp for Ibadan, and Makurdi; and 2 pieces of 80Wp for Kano and Maiduguri. The difference in the array requirement was based on the solar radiation available in the location, for those having higher radiation require less solar array and vice versa.

Keywords: Radiation, Photovoltaic, Street Lighting, Night Length, Performance Ratio.

INTRODUCTION

There is a desperate need for high-quality, affordable, and reliable lighting systems at sites where the electricity grid is either non-existent or unstable for applications such as road lighting, residential lighting, area lighting, and security lighting (Morakinyo *et al.*, 2014; Patel *et al.*, 2015). Nigeria is located between 4^{o}N and 14^{o}N latitude resulting in vast supplies of solar radiation all year round; and therefore, solar energy is a promising solution (Jadin *et al.*, 2015; Dike *et al.*, 2017). The solar street lighting system is a part of the complementary structure of the street consisting of: solar photovoltaic (SPV) module and its mounting pole, luminary (lamp), battery bank, and control electronics; placed or installed on the left or right side or in the middle part of the street to brighten the path or neighborhood of the street (Posadillo and Luque, 2008; Aung and Myint, 2014; Patel *et al.*, 2015; Arowosere and Akintade, 2018).

Many works have been carried out for standalone solar photovoltaic systems: Patel *et al.* (2015) propose the design and implementation of a technologically advanced, cost-effective, and smart LED street light using MPPT (Maximum Power Point Tracking) algorithm using LPC800 max board charge controller; Morakinyo *et al.*, (2014) designed and constructed a solar street light with automatic switching of luminaries (ON at night and OFF at dawn); Arowosere and Akintade (2018) taking the Nigerian Institute of Leather and Science Technology as a case study developed a moveable solar energy street light using a light-dependent resistor (LDR) in controlling the timing ON-OFF of the lamp. There are many solar street lights installed in various places but many systems fail within a short time (in less than two years) after installation. This cast doubts on the effectiveness and suitability of solar photovoltaic systems. The major cause of the failure is induced by poor design (wrong sizing/matching) of the components of the system (Aung and Myint, 2014; Emodi *et al.*, 2014; Dike *et al.*, 2017).

This work gives a detailed design and comparative analysis of Stand-alone Solar Street Lighting Systems taking six locations (Port-Harcourt, Benin-City, Ibadan, Makurdi, Kano, and Maiduguri) as cases for the study.

MATERIALS AND METHODS

Materials Used

The materials used for the analysis in this work are:

- the geographical Coordinates of the locations,
- the meteorological data of the locations, and
- the specification of the appliances used in the design.

The geographical coordinates of the locations used as case study are as shown in Table 1.

Table 1: Geographical Coordinates of the Locations

S/No.	Location	Latitude (°N)	Longitude (°E)	Altitude (metres above sea level)
1	Port-Harcourt	4.9	7.0	18
2	Benin-City	6.3	5.6	79
3	Ibadan	7.4	3.9	198
4	Makurdi	7.7	8.5	145
5	Kano	11.8	8.9	531
6	Maiduguri	11.9	13.2	337

The monthly average solar radiation data were obtained for all the locations based on 22 years of monthly average insolation figures using Irradiance Calculator (2018) from the National Aeronautics Space Administration (NASA) as shown in Table 2.

Table 2: Monthly Average Solar Radiation Data in kWh/m^2-day for the Locations

Locations	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
PortHarcourt	5.14	5.18	4.74	4.53	4.16	3.48	3.19	3.37	3.38	3.63	4.16	4.90
Benin-City	5.37	5.43	5.28	4.99	4.67	4.16	3.51	3.51	3.77	4.33	4.94	5.19
Ibadan	5.45	5.64	5.57	5.27	5.00	4.49	3.93	3.73	4.05	4.65	5.06	5.30
Makurdi	5.82	5.94	5.78	5.40	5.08	4.66	4.34	4.12	4.39	4.82	5.44	5.67
Kano	5.44	6.27	6.71	6.85	6.63	6.29	5.69	5.32	5.57	5.84	5.67	5.23
Maiduguri	5.56	6.24	6.62	6.52	6.24	5.85	5.32	5.05	5.49	5.83	5.79	5.31

In solar street lighting system, the lamp(s) can either be in AC or DC type but the former requires inverter while the latter does not require inverter which makes it more efficient and cheaper (Patel *et al.*, 2015; Arowosere and Akintade, 2018). A Block diagram of the later type (street lighting system using DC lamp type) is as shown in Figure 1.

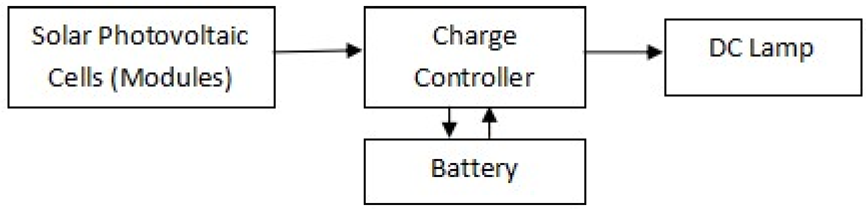

Figure 1: Block Diagram of Solar Street Lighting System using DC Lamp

The design was carried out based on the system components with specifications as:

i. Lamp(s): Single LED Lamp per stand rated 12V, 40W DC;
ii. Battery: 12V, 100Ah Lithium-ion Deep Cycle Battery;
iii. Module: 80W Monocrystalline module with specifications at the STC as Rated Power (P_{max}) = 80W, Rated Voltage (V_{mp}) = 17.5V, Rated Current (I_{mp}) = 4.57A, Open Circuit Voltage (V_{oc}) = 20.9V, and Short Circuit Current (I_{sc}) = 5.43A;
iv. Charge Controller: 12V/24V, 20A MPPT Charge Controller.

Experimental Design

The method used for this work is summarized in a block diagram as shown in Figure 2.

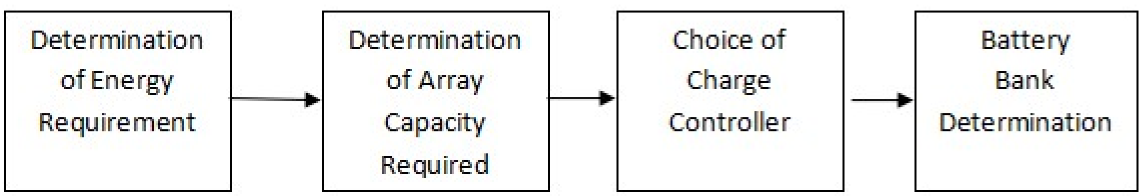

Figure 2: Block Diagram Summarizing the Method Used

Determination of Energy Requirement

The daily electrical energy consumed by the lamp(s) (E_{Req}) is the product of the total power rating of the lamp(s) (P_{Lmp}) and the daily hours of use i.e. hours from dusk to dawn (H_{Ngt}) expressed as:

$$E_{Req} = P_{Lmp} H_{Ngt} \quad (1)$$

The sum of day length hours (D_H) and night length hours (N_H) gives the complete daily hours written as:

$$H_{Day} + H_{Ngt} = 24 \quad (2)$$

The day length hours (H_{Day}) is given by (Kothari *et al.*, 2012; Agarwal *et al.,*2012; Duffie and Beckman, 2013):

$$H_{Day} = 2\,[\cos^{-1}(-\tan(Del)\tan(Lat))]/15 \quad (3)$$

Where: H_{Day} the day length hours; Lat the latitude of the location; and Del the declination angle.

Substituting H_{Day} from equation 3 into equation 2 and simplifying gives:

$$H_{Ngt} = [360 - 2\cos^{-1}(-\tan(Del)\tan(Lat))]/15 \quad (4)$$

There are many expressions derived for the determination of declination angles. One of the most widely used is the one by Cooper in 1969 as cited by Duffie and Beckman (2013) and Goswani (2015) given as:

$$Del = 23.45\sin[2\pi(d_n + 284)/365] \quad (5)$$

Where, d_n is the nth day of the year (Jan. 1=1; Dec. 31=365).
Recommended monthly average days suggested by Klein (1976) as cited in Duffie and Beckman (2013) can be used for the determination of the monthly average declination angle. The days and their corresponding day numbers are as shown in Table 3.

Table 3: Monthly average days and their day numbers

Month	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Ave Day	17	16	16	15	15	11	17	16	15	15	14	10
i^{th} Day	i	31+i	59+i	90+i	120+i	151+i	181+i	212+i	243+i	273+i	304+i	334+i
Day No	17	47	75	105	135	162	198	228	258	288	318	344

Source: Klein, 1977 as cited in Duffie and Beckman(2013)

Substituting the monthly average day numbers given in Table 3 into equation 5 gives the monthly angle of declination in degrees as **-20.92°, -12.95°, -2.42°, 9.41°, 18.79°, 23.09°, 21.18°, 13.45°, 2.22°, -9.60°, -18.91°,** and **-23.05°** for January to December respectively.

Array Capacity Sizing

The size of the solar array required can be calculated using the relation (Ishaq *et al.*, 2013; Guda and Aliyu, 2015; Saleh *et al.*, 2015; Raquibul *et al.*, 2016; Kingsley *et al.*, 2018):

$$P_{array} = E_{Req}/(SH_p \times \eta_{PR}) \quad (6)$$

Where: P_{array} the size of the array (modules) required; E_{Req} the energy required by the lamp(s); SH_p the peak sunshine hours (i.e.solar radiation in $kWh/m^2 - day$) for the location; and η_{PR} the performance ratio of the system which is evaluated from (Yasmeena and Das, 2015):

$$\eta_{PR} = \eta_{cable}\eta_{bat}\eta_{temp}\eta_{inv}\eta_{CC}\cdots \quad (7)$$

Where: η_{cable} is the wiring efficiency, η_{bat} the battery efficiency, η_{temp} the temperature correction factor, η_{inv} the inverter efficiency, η_{CC} the charge controller efficiency. It is sometimes assumed that: $\eta_{cable} \approx 95\%$; $\eta_{bat} \approx 90\%$; $\eta_{temp} \approx 88\%$; $\eta_{CC} \approx 92\%$; and since the inverter is not used in the system its efficiency (η_{inv}) ≈100%. Therefore,

$\eta_{PR} = \eta_{cable}\eta_{bat}\eta_{temp}\eta_{inv}\eta_{CC}\cdots = 0.95 \times 0.90 \times 0.88 \times 1.00 \times 0.92 \approx 0.6922$;

But by taking more factors (such as dust cover, mismatch factors, etc.) into consideration; the performance ratio can be assumed to be 65% i.e. $\eta_{PR} \approx 0.65$.

Choice of Suitable Charge Controller

The voltage rating of the charge controller must match with the system voltage; and its current rating must exceed the maximum input current expected from the array approximately evaluated from (Alshemmary *et al.*, 2013; Saleh *et al.*, 2015):

$$I_{MC} = M_{par} \times I_{Sc}^{M} \times F_{sft} \quad (8)$$

Where: I_{MC} the maximum input current from the modules (array) to the charge controller; M_{par} the number of modules in parallel; I_{Sc}^{M} the short circuit current of the module; and F_{sft} the factor of safety which is usually taken to be 25% (i.e. $F_{sft} = 1.25$).

Therefore, for two modules in parallel: $I_{MC} = M_{par} \times I_{Sc}^{M} \times F_{sft} = 2 \times 5.43 \times 1.25 \approx 13.6$ A; while for three modules: $I_{MC} = M_{par} \times I_{Sc}^{M} \times F_{sft} = 3 \times 5.43 \times 1.25 \approx 20.3$ A

Battery Bank Capacity Determination

Solar radiation is only available during the day, but in many cases, the usage is at night. This necessitates the need for storage. The best option for storage is to use a battery (Shepherd and Shepherd, 2007; Chapman, 2011; Sharma and Shakya, 2011; Ferron, 2016). The total capacity of the battery bank can be calculated using (Guda and Aliyu 2015;

Al-Shamani *et al.*, 2015; Raquibul *et al.*, 2016; El-Shemawy *et al.*, 2017):

$$B_{cap} = \{E_{Req} \times D_{cloud}\} / \{V_{sys} \times DoD_{max} \times \eta_{bal}\} \quad (9)$$

Where: B_{cap} the total capacity of the battery bank; E_{Req} the energy required by the lamp(s); D_{cloud} the number of continuous cloudy days; V_{sys} the system voltage; DoD_{max} the Maximum Depth of Discharge of the battery; and η_{bal} the efficiency of the balance of system components whose input energy is from the battery bank.

RESULTS AND DISCUSSION

Substituting the latitudes of the locations (shown in Table 1) and the corresponding monthly average declination angles into equation 4 gives H_{Ngt} (the monthly average length of the night of the location) in hours is shown in Table 4.

Table 4: Monthly Average Length of Night in Hours

Locations	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
PortHarcourt	12.25	12.15	12.03	11.89	11.78	11.72	11.75	11.84	11.97	12.11	12.22	12.28
Benin-City	12.32	12.19	12.04	11.86	11.71	11.64	11.67	11.80	11.97	12.14	12.29	12.36
Ibadan	12.38	12.23	12.04	11.84	11.66	11.58	11.62	11.76	11.96	12.17	12.34	12.42
Makurdi	12.39	12.24	12.04	11.83	11.65	11.56	11.60	11.75	11.96	12.17	12.35	12.44
Kano	12.61	12.37	12.07	11.74	11.46	11.32	11.38	11.62	11.94	12.27	12.55	12.68
Maiduguri	12.62	12.37	12.07	11.73	11.45	11.31	11.38	11.61	11.94	12.27	12.55	12.69

Substituting the power rating of the lamp ($P_{Lmp} = 40$W) and the corresponding H_{Ngt}(obtained in Table 4) into equation 1 gives the E_{Req} (average daily electrical energy) for the month in Wh/day as shown in Table 5.

Table 5: Monthly Average Energy Requirement in Wh/day

Locations	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
PortHarcourt	490.0	486.0	481.1	475.7	471.1	468.8	469.8	473.7	479.0	484.4	489.0	491.1
Benin-City	492.9	487.8	481.4	474.4	468.5	465.6	466.9	471.9	478.7	485.7	491.6	494.4
Ibadan	495.2	489.1	481.7	473.4	466.5	463.1	464.6	470.5	478.5	486.7	493.6	496.9
Makurdi	495.8	489.5	481.7	473.1	465.9	462.4	464.0	470.1	478.4	487.0	494.2	497.6
Kano	504.4	494.7	482.7	469.4	458.3	452.8	455.2	464.7	477.5	490.8	501.9	507.2
Maiduguri	504.6	494.8	482.7	469.3	458.1	452.5	455.0	464.6	477.5	490.9	502.1	507.4

Substituting the E_{Req} (shown in Table 5), $\eta_{PR} = 0.65$, and SH_p (shown in Table 2) into equation 6 gives the size of the solar array required (P_{array}) as shown in Table 6.

Table 6: The Size of the Array Required (W_p)

Locations	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
PortHarcourt	146.7	144.4	156.2	161.5	174.2	207.3	226.6	216.3	218.0	205.3	180.8	154.2
Benin-City	141.2	138.2	140.3	146.3	154.3	172.2	204.7	206.8	195.3	172.6	153.1	146.5
Ibadan	139.8	133.4	133.0	138.2	143.5	158.7	181.9	194.1	181.8	161.0	150.1	144.2
Makurdi	131.1	126.8	128.2	134.8	141.1	152.7	164.5	175.5	167.7	155.4	139.8	135.0
Kano	142.7	121.4	110.7	105.4	106.3	110.7	123.1	134.4	131.9	129.3	136.2	149.2
Maiduguri	139.6	122.0	112.2	110.7	112.9	119.0	131.6	141.5	133.8	129.5	133.4	147.0

Substituting E_{Req}(the values as shown in Table 5), $D_{cloud} = 1$, $V_{sys} = 12V$ (the voltage rating of the lamp), $DoD_{max} \approx 60\%$, and $\eta_{bal} \approx 95\%$ (the efficiency of the cables) into equation 9 gives the capacity of the battery bank required as shown in Table 7.

Table 7: The Capacity of the Battery Bank Required (Ah)

Locations	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
PortHarcourt	71.64	71.06	70.34	69.54	68.87	68.54	68.69	69.26	70.03	70.82	71.49	71.81
Benin-City	72.06	71.31	70.38	69.36	68.50	68.07	68.26	69.00	69.98	71.01	71.87	72.27
Ibadan	72.39	71.51	70.42	69.21	68.20	67.70	67.93	68.79	69.95	71.16	72.16	72.65
Makurdi	72.49	71.57	70.43	69.17	68.12	67.60	67.83	68.73	69.94	71.20	72.25	72.75
Kano	73.75	72.32	70.57	68.63	67.00	66.19	66.55	67.94	69.81	71.75	73.38	74.15
Maiduguri	73.78	72.34	70.57	68.61	66.97	66.16	66.52	67.92	69.81	71.77	73.40	74.19

From Table 4, it can be seen that the length of nights for all the locations varies with the months of the year with maximum values in December and minimum values in June. It can also be seen that among all the locations, the shortest night is 11.31 hours (i.e. 11 hours,18 minutes, and 36 seconds), while the longest night is 12.69 hours (i.e. 12 hours,41 minutes, and 24 seconds). It can also be evaluated that the variation between longest night and shortest night are: 0.56, 0.72, 0.85, 0.88, 1.36, and 1.37 hours for PortHarcourt (4.9^{o}N), Benin-City (6.3^{o}N), Ibadan (7.4^{o}N), Makurdi (7.7^{o}N), Kano (11.8^{o}N), and Maiduguri (11.9^{o}N) respectively; which shows that the range of day-length or night-length increases with increase in latitude (with places closest to equator having the least variation). From the table, it can be concluded that the length of hours from dusk to dawn in all locations in Nigeria will not exceed 13 hours.

From Table 5, it can be seen that the energy requirement is proportional to the length of the night; therefore, it is highest in December and least in June among all the locations. But Table 2 shows that variation in solar radiation is not uniform among the locations: it is least in July for PortHarcourt, and Benin-City; August for Ibadan, Makurdi, and Maiduguri; and December for Kano. Therefore, this confirms that there other factors such as cloud cover that control the availability of solar radiation apart from day length.

From Table 6, the maximum values of array requirement are 226.6W_p, 206.8W_p, 194.1W_p, 175.5W_p, 149.2W_p, and 147.0W_p for PortHarcourt, Benin-City, Ibadan, Makurdi, Kano, and Maiduguri respectively. Therefore, based on the 80Wp solar panel available, 2 pieces of the panels (to be connected in parallel) will be adequate for Kano and Maiduguri but in the other locations (PortHarcourt, Benin-City, Ibadan, and Makurdi) only 3 pieces of such panels also to be connected in parallel that will be adequate. An alternative arrangement is to use 2 pieces of 120Wp solar panel for PortHarcourt, and Benin-City; and 2 pieces of 100Wp for Ibadan, and Makurdi.

For the charge controller requirement, two pieces of the 80Wp solar panel in parallel produces a maximum current of 10.86A, while three pieces in parallel produce 16.29A. Therefore using the 12V, 20A charge controller for the 2 pieces solar panel has 9.14A (i,e. 84.16%) tolerance, while for 3 pieces the tolerance is 3.71A (i.e. 22.77%). Therefore, for all the locations, a piece of 12V, 20A charge controller will suffice.

From Table 7, the battery bank requirement at 60% maximum depth of discharge ranges from 66.2Ah to 74.2Ah. Therefore, a piece of 12V, 100Ah battery will be enough for all the locations. The operating depth of discharge will then be 39.7% to 44.5% with the condition that enough solar panels were installed.

CONCLUSION

The design of street light based on a 40W DC lamp used from dusk to dawn shows that a piece of 12V, 100Ah battery, and a piece of 12V, 20A charge controller will suffice for all the locations. The difference is based on solar array requirement in which the results show that 2 pieces of 120Wp solar panel connected in parallel will be adequate for PortHarcourt, and Benin-City; 2 pieces of 100Wp for Ibadan, and Makurdi; and 2 pieces of 80Wp for Kano and Maiduguri. The difference in the array requirement was based on the solar radiation available in the location, for those having higher radiation require less solar array and vice versa.

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