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ESTIMATION OF ROOFTOP SOLAR PHOTOVOLTAIC POTENTIAL OF A UNIVERSITY

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Abstract

The provision of steady electricity on campuses is one of the major challenges confronting Nigerian Universities. While electricity demand in Nigeria has been growing, the supply Has been fluctuating and decreasing over the years. University communities like industries which cannot function well without electric power have been worst hit. To address this problem renewable energy generation, particularly solar photovoltaic electricity, is a highly desirable policy shift. This paper examines the rooftop solar photovoltaic potential of the University of Benin. The data of residential and academic buildings, and rooftop types were obtained. A representative sample of the range of buildings in the study area was chosen for the analysis. The dimensions of rooftops were obtained from building plans and the slopes were calculated. Important terrain parameters and the solar radiation were estimated for the study area. These were then used to obtain the photovoltaic potential of the chosen sample. The PV potential was then extrapolated using linear regression to the entire study area. The total PV potential for the study area for one year was obtained as 9,470,116,545 kWh.

Keywords: University, Solar, Photovoltaic, Rooftop, Potential

1. Introduction

Concern is mounting in Nigeria and in the globe over conventional carbon-based energy production. The issues include increasing atmospheric carbon dioxide (CO_2) and other harmful gases concentrations from greenhouse gas emissions, environmental safety of energy production techniques, volatile energy prices, and depleting carbon-based fuel reserves to name a few [1]. This is leading to increasing challenge to diversify energy sources and bringing to the fore discussions on renewable generation policies.

It is important to note that electricity supply in Nigeria has been fluctuating, decreasing over the years while electricity demand has been growing due to population pressures, industrialization, and urban migration. The situation may get worse unless significant shift in energy policy and investment takes place urgently. Renewable energy generation, particularly solar photovoltaic electricity, is a highly desirable policy shift. Reduced transmission and distribution losses due to the possibility of decentralized generation and localized use of solar photovoltaic electricity and reduced carbon emission would be among the gains.

University of Benin is one of the largest Federal Universities in Nigeria land mass wise, it is located approximately on latitude 6º20′22.4″ (6.3396 º) north and longitude 5º36′31″ (5.6086 º) east elevation of 87meters or 285 feet; population density of about 40,000 students as at 2010 and 75,000 students recently. The University has average annual temperature of 26.1°C or 78.98°F. About 2025 mm of precipitation falls annually. Figures 1 and 2 show approximate Climograph and Temperature graph of University of Benin respectively [2]. The warmest month of the year is April, with an average temperature of 27.5°C while July has the lowest average temperature for the whole year of 24.5°C.

In order to increase the potential generating capacity of solar photovoltaic cells; more cladding is required that the entire roof of buildings can be mounted upon by PV cells and even windows and the facade in a way that its light will not be obstructed from entering the buildings.

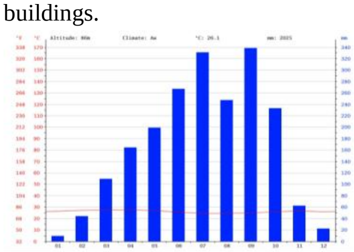

FIGURE 1 CLIMORAPH (APPROXIMATE) OF UNIVERSITY OF BENIN
(Source: Climate-Data.org)

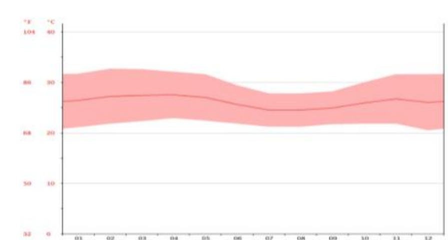

FIGURE 2 TEMPERATURE GRAPH OF UNIVERSITY OF BENIN
(Source: Climate-Data.org)

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2. Methodology

In order to estimate total rooftop photovoltaic potential for the study area the available data sources were identified. It was then necessary to identify a sample of buildings for which rooftops are to be analyzed. The terrain parameters and the amount of solar radiation were calculated for those rooftops. The rooftop types were classified and the average slope of each class was determined. Finally, the equations built were applied to calculate the PV potential of the entire study area.

2.1. Data collection and Building Rooftops Sample Set Isolation

Data of residential and academic buildings in the University of Benin were obtained from the Estate department. Dimensions and slopes of rooftops were obtained from the Physical Planning Division. The Service department provided relevant data on size (dimension), capacity, and efficiency of Solar panels to be used as reference and also for comparison in estimating electrical energy from solar energy.

The methods proposed by [3] were used to obtain a sample set of rooftops which was used to characterize the region. There were a total of 208 buildings in the study area (University of Benin). The study area comprised mainly of residential and academic buildings. Classes were created based on rooftops to ensure the sample chosen for analysis was representative of the range of buildings in the study area. Classification of the buildings in the study area is shown in Table 1. For sample selection the Cochran equation was used:

$$n_o = \left(\frac{(1.96)^2 pq}{e^2}\right) \quad (1)$$

Due to smaller sample size equation (2) was further used for adjustment.

$$n_r = \frac{n_o}{1+\frac{(n_o-1)}{N_r}} \quad (2)$$

e is the desired level of precision, 85% confidence level.

p represents a proportion of the population (buildings) which has the attribute in question, taken as 50%.

q is 1-*p*

n_o is the Cochran's sample size recommendation.

N_r is the population (buildings) size.

n_r represents the new adjusted sample size.

The number of buildings to be selected from each class is determined by their rated percentage (R%) . This was accomplished with equation (3).

$$\text{Sample size} = (R\%).n_r \quad (3)$$

Table 1. Building classifications by rooftops

Class	No of buildings	Types of rooftops
1	2	Hexagonal Gazebo
2	3	Hip and Valley
3	6	Box Gable
4	20	Cross hipped
5	21	Flat
6	60	Open Gable and Skillion and Lean to Roof
7	96	Hip and open Gable
Total	208	

2.2 Estimating Terrain Parameters and Incoming Solar Radiation

Slope of roof tops was calculated in degrees from 0 - 90°. It was determined by measuring inclined angle of the building rooftops with the horizontal with protractor from building roof plan. Dimensions which comprises of length and width of rooftops were measured in meters. The Solar radiation which reaches the ground is formed by direct radiation (I) and diffuse radiation (D) which together form the global radiation (G) [4]. Radiation is calculated in W/m². The solar radiation estimation was done monthly.

Direct solar flux is calculated using equation (4)

$$I = I_0 . C_t . \Gamma . \exp\left(\frac{-0.13}{\sin(h)}\right) . \sin(h) \quad (4)$$

I_0 is the solar constant, which is defined as the energy flux received by a unit area. I_0 is 1367 W/m² [5, 6], Γ obtained from equation (5) is the dimensionless turbidity atmospheric factor for clear skies [7, 8].

$$\Gamma = 0.796 - 0.01. \text{Sin}\,[0.986(j+284)] \quad (5)$$

C is the dimensionless correction of the earth–sun distance and it can be calculated using the equation given by [9].

$$C = 1+0.034.\cos\left(\frac{360}{365}(j-2)\right) \quad (6)$$

h in degrees is the height of the sun and can be calculated using the equation by [10].

$$h = \sin^{-1}(\sin(\varphi).\sin(\delta) + \cos(\varphi).\cos(\delta).\cos(\omega)) \quad (7)$$

δ in degrees is the solar declination which can be obtained by the approximate equation given by [11].

$$\delta = 23.45.\sin(0.986.(j+284)) \quad (8)$$

where j is the day number of the year, ranging from 1 on 1 January to 365 on 31 December.
φ in degrees is the latitude, in this case the value of φ is 6º20′22.4″ (6.3396 º) north:
ω in degrees is the hour angle of the sun and can be calculated using equation by [10, 12]:

$$\omega = 15(12 - T_{SV}) \quad (9)$$

T_{SV} (hours) is the true solar time of the study site and it is determined with the equation given by [13]:

$$T_{SV} = T_1 - DT_1 + (D_{hs} + E/60)/60 \quad (10)$$

where T_1 = local time.
DT_1= advance the local time through standard time.
D_{hs}= the time difference (advance of 4 min per degree).
E= equation of time, which is calculated by the equation given by [14]:

$$E = 450.8.\ \sin(2\pi j/365 - 0.026903) + 595.4.\ \sin(4\pi j/365 + 0.353) \quad (11)$$

E gives time in seconds.
Diffuse solar flux can be obtained by equation (12)

$$D = 120.\Gamma.\exp\left(\frac{-1}{0.4511+\sin(h)}\right) \quad (12)$$

Global solar flux is the sum of the direct and diffuse solar radiation [15, 16]:

$$G_{h} = I + D \quad (13)$$

Since rooftops are inclined and oriented surfaces, formulae for solar radiation on inclined and oriented surfaces will be used.
Direct solar flux for an inclined receiver can be calculated by the equation of [17]:

$$I_\theta = R.I \quad (14)$$

θ is the angle of incidence of solar radiation on a receiver inclined at an angle i with the horizontal measured in degrees and oriented at an angle γ with the south, it is determined by the equation of [18, 19]:

$$\cos\theta = \sin i \cos(\psi-\gamma).\ \cos h + \sin h.\ \cos i \quad (15)$$

R_1 is the dimensionless ratio of the direct solar flux and ψ is azimuth of the sun measured in degrees. R is calculated by the empirical equation of [20]

$$R = \sin I.\left(\frac{\cos(\psi-\gamma)}{\tan(h)}\right) + \cos i \quad (16)$$

If the ground is considered to be horizontal (i = 0), it receives the diffuse radiation by the sky, and if it is inclined at an angle **i**, it sees less air but against the ground receives a fraction of the quantity $a^*.G_h$ where a* is ground albedo [20, 21].
Finally, the diffuse flux for inclined receiver, D is determined in accordance with Bernard [20]

$$D = 0.5(1+\cos i).D + 0.5(1-\cos i).a^*.G_h \quad (17)$$

a* is the ground albedo of the study position and it has an approximate constant value of 0.2 according to [22].
Global solar flux being the sum of the direct and diffuse solar radiation.

$$G_\theta = R_G.G \quad (18)$$

R_G is the dimensionless ratio of the global solar flux which can be calculated by the empirical equation of [20]

$$R_G = (R - \tfrac{1}{2}(1+\cos i)).\left(\frac{I_h}{G_h}\right) + \tfrac{1}{2}(1+\cos i) + \tfrac{1}{2}(1-\cos i).a^*.G_h \quad (19)$$

$$G_\theta\,(kWh/m^2) = G_\theta\,(kW/m^2).Hr_v \quad (20)$$

Hr_v is the monthly duration of sunshine measured in hours and it is determined by the product of monthly average hour per day (Hr) and date of each month as recommended by [23].

2.3 Calculation of PV Potential on Building Rooftops

Calculating the PV potential requires a consideration of different output capacities, type of panels or system in place. Equation (21) which was suggested by [24] was used for estimating the PV potential.

$$E_R = 365P_K.r_P.G_\theta \quad (21)$$

E_R is the monthly potential for electricity generation in kilowatt hours (kWh) per unit area.
This equation incorporates both the peak power rating for the panel type and a system performance ratio. The peak power rating is a reflection of the efficiency of the PV technology under consideration. Yearly average performance ratio of 0.75 was used [25]. Table 2 shows the relevant solar panel data.

Table 2. Solar panel data

Type	Mono-crystalline silicon
Dimension	153cm by 80cm
Area	12240cm²
Peak power	230Watts
Peak power rating(P_K)	18.8%

The total PV output potential for the study area was calculated by applying the average incoming solar radiation to the Súri formula. When coupled with the total rooftop area, the equation provides a means of determining the total capacity (kW) and monthly energy output (kWh) potential for the study area.

The area of the rooftops can be determined from equation (22)

Area (A) = L x W (22)

where L and W represent length and width of rooftops.

Taking Q to represent total PV potential for each month of the year, equation (23) is applied.

$Q = N.\ A_v.\ E_R$ (23)

where N represents number of buildings and A_v represents average rooftop area of each class which can be determined by using equation (24)

$$A_V = \left(\frac{\sum A}{N}\right) \quad (24)$$

2.4 Statistical Analysis for Extrapolation to Study Area

Simple linear regression was run to identify a linear fit equation for rooftop area. This linear fit equation was the basis for extrapolating from the rooftop area in the sample set to the rooftop area in the entire study area. No of sample buildings and total area of sample buildings in each class are used in the analysis to obtain the total area of buildings in each class. Total PV potential (Q) was determined by summing the values of Q of each class for the twelve months of the year.

3.0 Results and Discussion

3.1. Determination of Sample Size for the Study.

The adjusted sample size obtained with equation (2) was used to determine the sample size using equation (3). The area of the buildings in the sample size were obtained from the building dimensions. Slope of the different rooftop classes were determined. It can be seen that classes 1, 3, 4 and 6 have slope of 15°, classes 2 and 7 have slope of 30° while class 5 have slope of 3°. Table 3 displays the breakdown of the number of samples and the areas to be analyzed as obtained from equation (3).

Table 3 Sample building and area for analysis with n_r=36

Class	Slope (°)	Rated Percentage (R%)	Sample size	Average Area of Analyzed samples (m^2)	Total Area of Analyzed Samples (m^2)
1	15	0.96	1	227.67	227.67
2	30	1.44	1	313.54	313.54
3	15	2.88	1	208.98	208.98
4	15	9.62	3	234.46	703.38
5	3	10.05	4	467.97	1871.88
6	15	28.85	10	378.19	3781.90
7	30	46.20	16	355.32	5685.12
Total		100.00	36	2186.13	12792.47

3.2 Estimation of Global Radiation in Study Area.

The global radiation in the study area was determined for the different months of the year using equations (4)-(13). The relevant parameters from the study area which had to be determined in order to estimate the solar radiation as well as the values of the solar radiation obtained for the study area are shown in Table 4a and 4b.

Table 4a. Terrain Parameters and Solar Radiation of Study Area.

Month	Γ	C□	δ(°)	h(°)	E(secs)
January	0.8049	1.0328	-20.9337	59.4798	11.8390
February	0.8015	1.0240	-12.9886	66.2516	26.6315
March	0.7970	1.0099	-2.4618	73.6239	40.4315
April	0.7920	0.9924	9.3709	76.0287	55.2067
May	0.7880	0.9768	18.7610	71.7657	69.9674
June	0.7862	0.9681	23.0762	68.7173	83.2365
July	0.7870	0.9673	21.2091	70.1543	100.9007
August	0.7902	0.9764	13.5066	74.8868	115.5922
September	0.7950	0.9918	2.2834	75.9841	130.2536
October	0.8001	1.0094	-9.5350	69.2594	144.8812
November	0.8040	1.0245	-18.8680	61.5715	159.4711
December	0.8058	1.0323	-23.0352	57.8826	172.0823

Table 4b. Values of Terrain Parameters and Solar Radiation of Study Area.

Month	T□$_v$(hr)	ω(°)	I_h (kW/m²)	D_h (kW/m²)	G_h (kW/m²)
January	11.0700	13.9507	0.9790	0.0966	1.0756
February	11.0741	13.8890	1.0270	0.0962	1.1232
March	11.0779	13.8315	1.0558	0.0956	1.1514
April	11.0820	13.7700	1.0426	0.0950	1.1376
May	11.0861	13.7085	0.9994	0.0946	1.0940
June	11.0898	13.6532	0.9694	0.0943	1.0637
July	11.0947	13.5796	0.9788	0.0944	1.0732
August	11.0988	13.5184	1.0183	0.0948	1.1131
September	11.1028	13.4573	1.0458	0.0954	1.1412
October	11.1069	13.3963	1.0324	0.0960	1.1284
November	11.1110	13.3355	0.9902	0.0965	1.0867
December	11.1145	13.2830	0.9631	0.0967	1.0598

Table 5 Monthly duration of sunshine

Month	Hr(hour)	Date	Hr_v(hour)
January	11.80	17	200.60
February	11.91	16	190.56
March	12.12	16	193.92
April	12.25	15	183.75
May	12.40	15	186.00
June	12.48	11	137.28
July	12.43	17	211.31
August	12.32	16	197.12
September	12.13	15	181.95
October	11.95	15	179.25
November	11.83	14	165.62
December	11.76	10	117.60

Table 5 shows the monthly duration of sunshine as presented by [26]

Table 6 values of R_i, and R_G by months for the different classes

Month	**i = 3° (Class 5)**		**i = 15° (Class 1, 3, 4 & 6)**		**i = 30° (Class 2 & 7)**	
	R□	$\mathbf{R_G}$	R□	$\mathbf{R_G}$	R□	$\mathbf{R_G}$
January	1.0204	1.0174	1.0738	1.0636	1.0745	1.0667
February	1.0149	1.0134	1.0464	1.0430	1.0216	1.0254
March	1.0095	1.0088	1.0197	1.0201	0.9699	0.9803
April	1.0078	1.0072	1.0115	1.0122	0.9540	0.9654
May	1.0108	1.0094	1.0262	1.0239	0.9825	0.9894
June	1.0130	1.0110	1.0372	1.0320	1.0037	1.0060
July	1.0120	1.0102	1.0320	1.0280	0.9936	0.9979
August	1.0086	1.0077	1.0154	1.0150	0.9615	0.9716
September	1.0079	1.0072	1.0116	1.0124	0.9543	0.9657
October	1.0126	1.0114	1.0352	1.0332	0.9999	1.0064
November	1.0187	1.0161	1.0650	1.0569	1.0574	1.0534
December	1.0219	1.0183	1.0808	1.0682	1.0880	1.0760

Rooftops are inclined and oriented surfaces. Equations (14)-(20) for solar radiation on inclined and oriented surfaces were employed.These equations were used to determine the monthly average daily global radiation on the inclined surfaces (rooftops) taken into consideration the different slope values. The monthly duration of sunshine, Hr_v measured in hours, the date and the no of hours used for the calculation as recommended by Klein (1977) are shown in Table 5.

Dimensionless ratio for solar radiation on a receiver inclined at angle i (R_i) and the dimensionless ratio of global solar flux (R_G) which are important parameters for the determination of global solar radiation are tabulated in Table 6 for the different types of rooftops and slopes. The monthly average daily global radiation on an inclined surface for the different types of rooftops and slopes are presented in Table 7.

Table 7. Monthly Average Daily Global Radiation on an Inclined Surface (G_0) for the different classes of rooftops

Month	i = 3° (Class 5)		i =15° (Class 1, 3, 4 & 6)		i = 30° (Class 2 & 7)	
	G_0 (kW/m^2)	G_0 (kWh/m^2)	G_0 (kW/m^2)	G_0 (kWh/m^2)	G_0 (kW/m^2)	G_0 (kWh/m^2)
January	1.0943	219.5166	1.1440	229.4864	1.1473	230.1484
February	1.1382	216.8954	1.1715	223.2410	1.1517	219.4680
March	1.1615	225.2381	1.1745	227.7590	1.1287	218.8775
April	1.1458	210.5408	1.1514	211.5698	1.0982	201.7943
May	1.1043	205.3998	1.1202	208.3572	1.0824	201.3264
June	1.0754	147.6309	1.0978	150.7060	1.0700	146.8896
July	1.0842	229.1023	1.1033	233.1383	1.0710	226.3130
August	1.1217	221.1095	1.1298	222.7062	1.0815	213.1853
September	1.1494	209.1333	1.1553	210.2068	1.1021	200.5271
October	1.1413	204.5780	1.1659	208.9876	1.1356	203.5563
November	1.1042	182.8776	1.1486	190.2311	1.1447	189.5852
December	1.0792	126.9139	1.1321	133.1350	1.1404	134.1110

Using the rooftop slopes of buildings in the university, terrain parameters, solar radiation in the study area and by applying relevant equations the amount of solar radiation that can be received per unit area of rooftops for the twelve months of the year was estimated.

3.3 PV Potential on Building Rooftops

The monthly potential for electricity generation in kilowatt hours (kWh) per unit area is obtained with equation (21). The peak power rating and performance ratio of the particular panel type is utilized with the monthly average daily global radiation values in Table 7. The monthly PV potential per unit area for different types of rooftops is shown in Table 8.

Table 8 Monthly PV potential per unit area for different values of i

Month	E_R(kWh/m²)		
	i = 3° (Class 5)	**i = 15° (Class 1, 3, 4 & 6)**	**i = 30° (Class 2 & 7)**
January	11297.420	11810.520	11844.590
February	11162.520	11489.100	11294.920
March	11591.880	11721.620	11264.530
April	10835.480	10888.440	10385.340
May	10570.900	10723.100	10361.260
June	7597.825	7756.084	7559.673
July	11790.750	11998.460	11647.200
August	11379.400	11461.570	10971.580
September	10763.050	10818.290	10320.130
October	10528.610	10755.540	10476.020
November	9411.795	9790.245	9757.004
December	6531.625	6851.791	6902.025

3.4. Extrapolation to Study Area

Linear fit equation for rooftop area was obtained by running simple linear regression. The linear fit equation was used to extrapolate from the rooftop area in the sample set to the rooftop area in the entire study area. The total study areas calculated by using sum of the class areas and regression analysis are presented in Table 9.

Table 9 Rooftop area calculated using regression analysis

Class	No of buildings	Total Area
1	2	668.46
2	3	1037.26
3	6	2143.65
4	20	7306.83
5	21	7675.63
6	60	22058.75
7	96	35335.48
Total	208	76226.06 (Sum of classes)
		76640.87 (Regression analysis)

From simple linear regression analysis the total area of rooftops equals 76 640.87m² which is in the same range as 76 226.06m² calculated from sum of classes. Table 10 shows the total PV potential for the various classes for the different months of the year. The annual PV potential is 9 470 116 545 kWh for the entire study area when the values for each of the classes are summed up.

Table 10 Total PV potential for classes

Month	Q(kWh)							Total
	Class 1	Class 2	Class 3	Class 4	Class 5	Class 6	Class 7	
January	7894859	12285915	25317616	86297444	86714823	260525255	418534113	897570025
February	7680004	11715767	24628611	83948905	85679379	253435198	399111351	866199215
March	7835433	11684248	25127048	85647874	88974969	258564252	398037632	875871456
April	7278485	10772298	23340998	79559958	83169137	240185310	366970992	811277178
May	7167965	10747325	22986579	78351889	81138323	236538243	366120234	803050558
June	5184632	7841347	16626329	56672386	58318092	171089515	267124683	582856984
July	8020492	12081175	25720505	87670728	90501429	264671092	411559407	900224828
August	7661604	11380382	24569603	83747772	87344068	252827994	387686078	855217501
September	7231597	10704656	23190636	79047435	82613164	238638042	364666662	806092192
October	7189652	10866361	23056124	78588938	80813694	237253877	370175346	807943992
November	6544387	10120550	20986859	71535659	72241459	215960575	344768412	742157901
December	4580148	7159195	14687842	50064873	50134338	151141948	243886371	521654715
								9,470,116,545

Conclusion

The national power utility in Nigeria is beset by severe problems which include generation, transmission, distribution, revenue collection, among many others. Introduction of solar PV electricity into the national power agenda has been examined and found to be capable of surmounting many of the problems currently faced by the utility; besides the obvious environmental benefits of renewable energy. Most Universities in Nigeria burn diesel oil in MW-sized internal combustion engines for power generation and many commercial and domestic consumers similarly have small private diesel or petrol generators. Replacing these with solar PV has the added benefit of no noise pollution in addition to environmental ones. The great advantage of solar PV electricity in Nigerian Universities would be the minimal maintenance cost of the system compared to that of conventional power stations. It would be appropriate for utility and governments to initiate a national solar PV programme similar to those of Germany, Japan, and the USA, with well designed reducing subsidies over one or two decades.

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