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TROPICAL DAYLIGHT AVAILABILITY AND SKY TYPOLOGIES FOR DAYLIGHTING EVALUATION AND DESIGN

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Abstract:

Daylighting in buildings is a critical functional requirement in the tropical climate. It has numerous benefits, whereas poor implementation is bound to create high energy consumption and user's discomfort, unlike in the temperate region. Daylight data for design is fundamental toward achieving optimal daylighting due to variations for different locations. Like most regions in the tropics, Nigeria has limited data in this regard. Therefore, this study investigated the availability of daylight and skies using daylight modelling methods. The global illuminance and irradiance data were input to model the outdoor daylight and sky types. The modelled, measured, and RadianceIES outdoor illuminance data were comparatively analysed relative to the design time and date. The results show that the sky is predominantly intermediate. More so, the monthly mean outdoor illumination varies from 47 to 67 klux at noon and as low as 9 klux during the morning and late afternoon. The study concluded that the mean outdoor illuminance for design is 30.7klux, 60.0klux, and 46.0klux at 0900, 1200, and1500 hours, respectively. In architecture, the use and applications of these data are to improve thermal, visual comfort, low-

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energy and task illuminance design in buildings, thus resulting in enhanced performance, cost savings, and user satisfaction.

Keywords:

Daylight, Makurdi Illuminance, Intermediate Sky, Daylight Modelling, Irradiance, Nigeria Sky

Introduction

Daylight and solar radiation are fundamental for living and the sustenance of living things. More so, it is entirely free. Daylight for humans is critical for visual and thermal comfort, health, performance, and psychological balance (Kittler, Kocifaj, and Darula, 2011; Knoop et al., 2020; Mead, 2008; Zain-Ahmed, Sopian, Abidin, and Othman, 2002). The optimal application of daylighting will minimise the dependence on artificial lighting, in addition to the advantages of daylight for humans,30 to 40 per cent of artificial lighting energy can be saved (Carletti, Cellai, Pierangioli, Sciurpi, and Secchi, 2017; Semprini et al., 2016). In building design, considering daylighting as a criterion, daylight data are essential (García, de Blas, and Torres, 2020). Daylighting strategies and technologies' efficiency rely on outdoor illuminance's comparative aspect. More so, daylight simulations have become a useful instrument for the daylighting design process. Therefore, data on the sky's conditions and the corresponding illuminance patterns and luminance distribution are essential to thermal, energy, and daylighting environmental studies. (Diakite-Kortlever and Knoop, 2021; Lou et al., 2020). Hence the study investigates the Makurdi tropical daylight availability and sky type for an enhanced daylighting evaluation and design.

Literature Review

The sun's energy is referred to as solar radiation. Daylight is a portion of the spectrum of the energy of the visible waveband from the solar electromagnetic radiation produced and incident on the surface of the earth following absorption distribution through the atmosphere. Its direct component is sunlight, whereas the cumulative luminous spectrum from the sky's dome is daylight. Daylight and solar radiation have some identical properties that require interdependence in modelling.

Daylight and solar availability modelling consider the slope irradiation and illumination based on hourly, daily, or/ and monthly averages, depending on the concept of investigation (Li and Lou, 2018). Daylight is often influenced by propagation due to sunlight's absorption and dispersion in the atmosphere, usually consisting of three components; direct, diffused, and reflected. The solar radiation unit is Watts per unit meter square (W/m2), and it's the number of joules originating from the sun. Figure 1 shows the schematic representation of the propagation from solar radiation to illuminance.

Luminance refers to the number of joules found in the visible radiation between 0.39 to 0.78µm wavelength (Gooch, 2011; Zain-Ahmed et al., 2002), and its unit is lm/m2. The accumulated incident surface energy in a specified time frame on a surface is irradiation, and its unit of measurement is Wh/m2 (product of watt and hour per metre square area) or (J/m2) joule per metre square area (González-Rodríguez et al., 2017). The instantaneous event energies are illuminance and irradiation. Luminous efficacy, on the other hand, referred to the ratio of illuminance (lumen per unit area) and the irradiance (Watt per unit area) denoted by K (Wattan and Janjai, 2015). The mathematical relationship between irradiance and illuminance is shown in equation (1) (García et al., 2020). The unit of Luminous efficacy is lm/W.

$$K=\frac{\text{Illuminance}}{\text{irradiance}} \qquad (1)$$

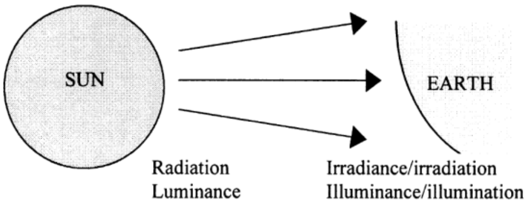

Figure 1: Sun Emitting Luminance /Radiation And The Surface Of The Earth Receiving Illumination And Irradiation

A previous study of solar energy mapping for Benue State, Nigeria, was carried out. It agrees that the state has potentials for renewable energy harvest from solar as presented on the average annual Iso radiation map in Figure 2 (Abur and Duvuna, 2014); however, the study only considered radiant energy.

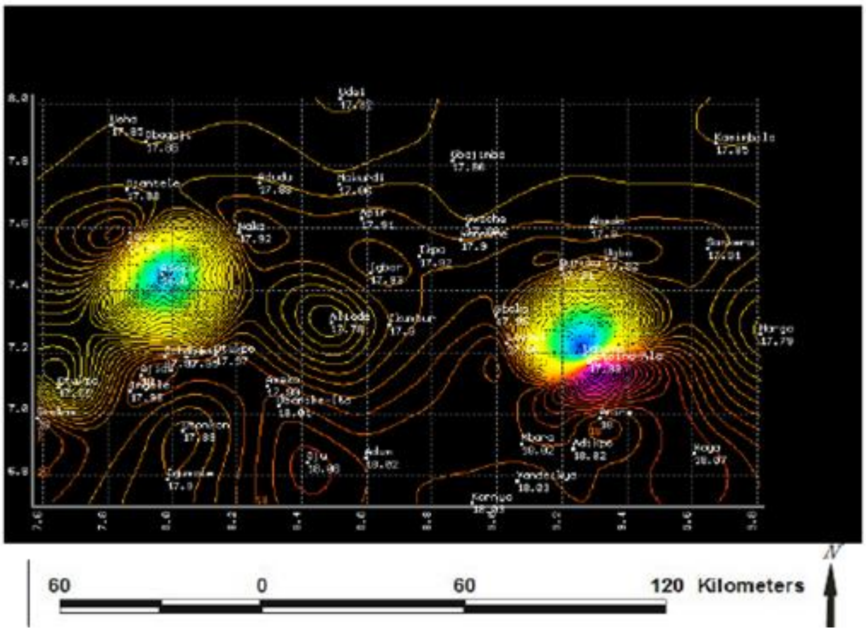

Figure 2: The Average Annual Iso Radiation Map Of Benue State-Nigeria (Abur And Duvuna, 2014)

The electricity consumption per capita in Nigeria is the lowest in Africa, accompanied by the epileptic power supply (Ayoosu, 2016; Emovon, Samuel, Mgbemena, and Adeyeri, 2018); therefore, daylighting in the built environment became critical as a design criterion and its influence on the indoor environment. The investigation of tropical daylighting variables towards the comprehension of daylight availability, the formations of clouds, and the distribution of luminance and irradiance are prime for an effective design for daylighting (Alshaibani, Li, and Aghimien, 2020). Data of illuminance and cloud cover based on long-term estimation or measurement are desirable for the reliable prognosis of daylighting performances for indoor and outdoor environmental design. Therefore, a new investigation was initiated to assess the variations of sky ratio, daylight illuminance and irradiance for tropical daylighting. Grounded on the local climate, a practical analysis of daylight availability in Makurdi-Nigeria was presented to assist early-stage daylighting development, analysis, and design.

Daylighting Design Time and Date

In tropical daylighting and thermal comfort design, the design time and dates are 0900, 1200, 1500 hours for 21 March, 22 June, 22 December (Ayoosu, Lim, Leng, and Idowu, 2021). These are due to the sun movement pattern, which creates equinox and solstices: equinox (March), summer solstice (June) and winter solstice (December), as shown in Figure 3. Therefore, it requires specific location illuminance availability for an optimal tropical daylighting design decision, including the sky type for simulations studies towards optimisation as most of the computer simulation software available is for the temperate climate.

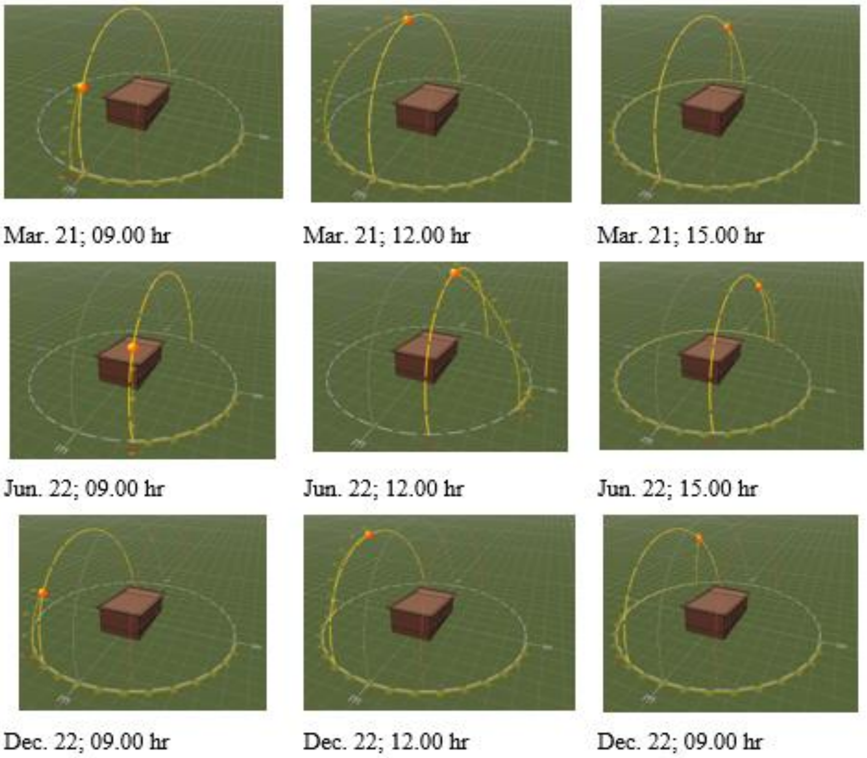
Mar. 21; 09.00 hr
Mar. 21; 12.00 hr
Mar. 21; 15.00 hr
Jun. 22; 09.00 hr
Jun. 22; 12.00 hr
Jun. 22; 15.00 hr
Dec. 22; 09.00 hr
Dec. 22; 12.00 hr
Dec. 22; 09.00 hr

Figure 3: Design Date, Time And Sun-Path Diagram For Equinox (March), Summer Solstice (June) And Winter Solstice

Materials and Methods

Makurdi Tropical Sky

The study employed the Nigerian Meteorological Agency, Makurdi Airport in Benue state, Nigeria. The data collected were global and diffused irradiance and data of cloud cover. The nebulosity index (NI) method was used to evaluate the sky's condition (Lim, 2019) for Makurdi, which lies on 7.7411o N, 8.5121oE, and an elevation of 114m AMSL. Those mentioned above long-term meteorological data within the nine years (1999-2008) were the input data. The mathematical relationship of the solar geometry, global irradiation I, diffuse irradiation, Id, and the diffuse illuminance as shown in equation (2) pave the way for NI evaluation based on the monthly averages.

$$NI=\frac{1\text{-}I_d/I}{1\text{-}CR} \quad (2)$$

CR denotes the cloud ratio, as is calculated from equation (3)

$$CR=\frac{I_{d,\,cl}}{[I_{d,\,cl}+\exp\ (\text{-}4mAR)\ \sin\alpha]} \quad (3)$$

Id,cl denotes diffused illuminance for the clear sky as represented by equation (4)

$$I_{d,\,cl} = 0.0065+(0.255\text{-}0.138\sin\alpha)\sin\alpha \quad (4)$$

$$Ar= \{5.4729+om[3.0312+om\{\text{-}0.6329+om\ (0.091\text{-}0.00512om)\}]\}^{-1} \quad (5)$$

Ar denotes Rayleigh's scattering coefficient, and om, on the other hand, represents the optical air mass, while the solar altitude is denoted by α.

Makurdi Tropical Sky

The general outdoor illuminance Prediction Model (Perez, Ineichen, Seals, Michalsky, and Stewart, 1990) was adopted and applied to model outdoor illumination data for Makurdi-Nigeria. The model required only data on solar radiation as an input variable (Y. W. Lim, 2019). The other models requiring climate data inputs, like turbidity, were not adopted because the data are not readily accessible. CIE clear sky and standard overcast models are specific to the locality. Hence, a universal lighting model has been established for other areas where the data on daylight is not commonly accessible (Igawa, Nakamura, and Matsuura, 1999). In this model, the global horizontal illumination over a given period is generally based on the sum of three components of solar illuminance, the direct Eb, diffuse Ed, and the reflected Eg components, which is essentially represented by equation (6).

$$E_G=E_b+E_d+E_g \quad (6)$$

DuMortier Perraudeau Page (DPP) model (Djamila, Ming, and Kumaresan, 2011) is developed for all-sky typology global luminous efficacy (Lim, 2019) as expressed in the equations (7).

$$K_G=(K_B I_b+K_D I_d)/I_g \quad (7)$$

$$I_b =(I_g\text{-}I_d) \quad (8)$$

Ib, Id, and Ig signify the direct, diffuse, and reflected components of the sun's hourly irradiation, respectively.

As presented, the diffuse luminous efficacy for the all-sky model re-counts to the beam as represented in equation (9) (Lim,2019).

$$K_D = 144 - 29\ CC\ /\ 8 \tag{9}$$

Where CC represents the cloud cover, and the oktas is the unit.
Several researchers agreed with a single value average of efficacy for the direct luminous component (Lim, 2019) and are in the range of 93 to 115 lm/W. However, 104 lm/W is the average value recommended (Muneer, 1995), and the value recommended was a factor for evaluating luminous beam efficacy, KB as shown in equation (10).

$$K_B = 104\ \mathrm{lm}\ /\ \mathrm{W} \tag{10}$$

More so, to compare with on-site illuminance level, a digital light meter (HOBO Pendant Temperature/Light Data Logger) was employed, as shown in Figure 4. The equipment is for the measurement of both illuminance and temperature in an environment (Becek, Salim, and Odihi, 2020). The device's merit was its selection criteria. It has a considerable capacity range for data storage, approximate logging duration between 1-360 years depending on the interval's events (battery life span up to one year) and illuminance measuring range of 0- 320,000 lux. The light device sensor was mounted horizontally facing the sky in an unobstructed open area. It was because the sensor's response depends on the vertical angle. For accuracy precaution, three of the devices were set up simultaneously and site to obtain a similar result, and the average was taken. The site was 6 km away, west of the metrological station. The outdoor illumination data were taken within 21 days at ten-minute intervals from 3-24, 2019. March was selected due to the non-availability of rainfall and dust-free sky to secure the device from rain effects and dust obstruction on the light sensor.

The RadianceIES, on the other hand, the weather data set of Makurdi annual meteorological year (AMY 2019) was saved on the C:\Program Files(x86)\IES\Shared Content\Weather of the integrated environmental solution- Visual environment (IES-VE) software installed on the Hp laptop computer. Then the Makurdi simulation weather file is selected in the ApLocate on tools menu of the software. The RadianceIES engine was activated where the outdoor illuminance data were generated in the Sky/eye menu summary under the sky condition; the intermediate sky with the sun. The illuminance data are usually monthly averages. The generated outdoor illuminance data for 21 March at 0900, 1200, and1500 hours were then compared with the modelled and the measured outdoor illuminance of Makurdi. The Pearson correlation was used to determine the strength of the mutual relationship.

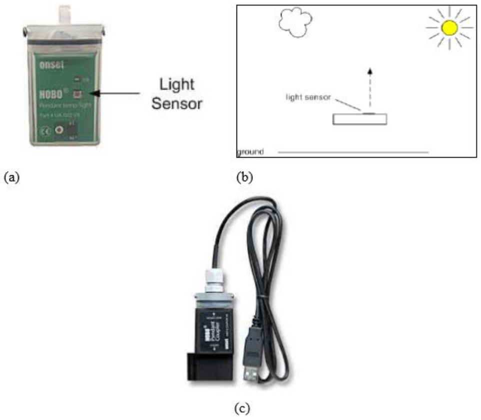

Figure 4: HOBO Digital Meter; (a) HOBO Data Logger, (b) Light Sensor Position, and (c) Pendant Optic USB Base Station and Coupler for Computer Connection

Main Results

The global solar irradiation data acquired from the Nigerian Meteorological Agency, Makurdi Airport, from 1999-2008 were the primary input parameters in the modelling process. The method (nebulosity Index) as in equation (2) was evaluated, and the result shows that the intermediate sky was predominant. For the nebulosity Index range of 0.05 and 0.95, the spectrum of indices indicates a typical intermediate with the sun. It was revealed that 74.0 per cent of the daytime was the predominantly intermediate sky, 20 per cent clear sky, and 6.0 per cent overcast. The distribution of the types of the sky is shown in figure 5. The months where the overcast sky was frequent was between August and September, as shown in Fig. 6, whereas the clear sky was experienced between December and January. The monthly NI value was highest in August and least in January, as shown in figure 6. This data is very useful for developing an efficient tropical daylighting design, as most existing luminance empirical models developed for overcast and clear skies are more appropriate for the temperate region. The model's accuracy is imperative, particularly when simulation and design outcomes are needed to model illumination data that are presently not available for many tropical regions like Nigeria.

On the other hand, the luminous efficacy values permitted the calculation of atmospheric exterior illuminance values for the entire months of the year using the luminous efficacy concept. It is defined by the ratio of luminance to irradiance. Afterwards, the direct and diffuse illumination was obtained by the product of their corresponding luminous efficacies. The hourly global illumination was the addition of the hourly direct and diffuse illumination. The average yearly value of KD was found to be 122 lm/W, and KG was 117lm/W in Makurdi. Figure 7 illustrates the modelled levels of outdoor illuminance for the entire months of the year, where the global illuminance was found highest in March, the mean was obtained in June, and the minimum was in August. Coincidentally, these progressively coincided with the hottest to the coolest range of the year. The hourly mean global illuminance exceeds 67,000 lux in March, where peak illumination was derived, and in August, the peak illumination value was at 43,600 lux. In June, the mean values of the year were recorded. More so, during the rainy months of July-September and the Harmattan (dust haze from northeast trade wind) in months of December-January/ February, when clear sky conditions were found, the global illumination ranges from 32.0 to 67.0 klux hours within the local time hours of 11:00 – 15:00. Even though bright clouds are more likely to appear for February and March's relatively less humid months, the values range from 52.0 to 62.3 klux. Whereas, monthly mean hourly irradiance peaked in November with the value of 793 W/m2 at noon, while the least value of 425 W/m2 was recorded in August at noon, as shown in Figure 8.

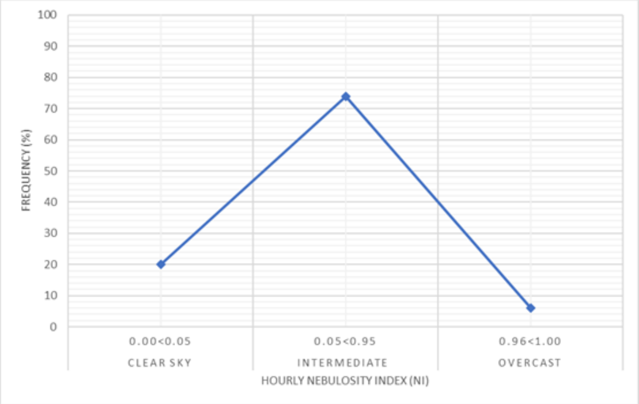

Figure 5: Makurdi Skies Based on Nebulosity Index Range

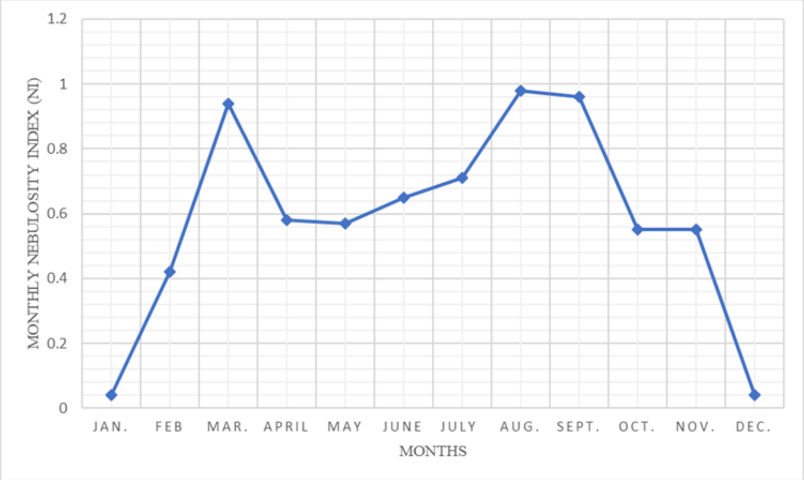

Figure 6: The Sky Nebulosity Index (NI) at Makurdi-Nigeria Based on Months Of The Year

The modelled monthly outdoor illuminance and irradiance are presented in figure 7 and figure 8, respectively. The outdoor illuminance might get up to approximately 80,000 lux on an average basis through the peak months at noon, and during the cloudy months, it may reach 45,000 lux. The month with peak value was May, whereas the minimum value was August. On the other hand, the irradiance may get to 800 W/m2 at noon in November and February. The month of August has the least irradiance, with the peak value of 485W/m2 at noon.

The on-site measured data (illuminance) were then plotted against the modelled values for comparison, as presented in figure 9. The outdoor illuminance data were taken over 21 days, set at ten minutes intervals in March 2019. It was using the average of the data from the three data logger and the model data, as shown in figure 9. It is significant to note that the values modelled were based on nine (9) years of collected data. In contrast, the on-site illumination measurement was based on the short duration in March 2019, which the values were considerably higher. However, the values show little disparity between the modelled and the measured illuminance thought with a similar pattern. Therefore, the disparity may be due to the short-term measurement as such long-term measurement may be desirable.

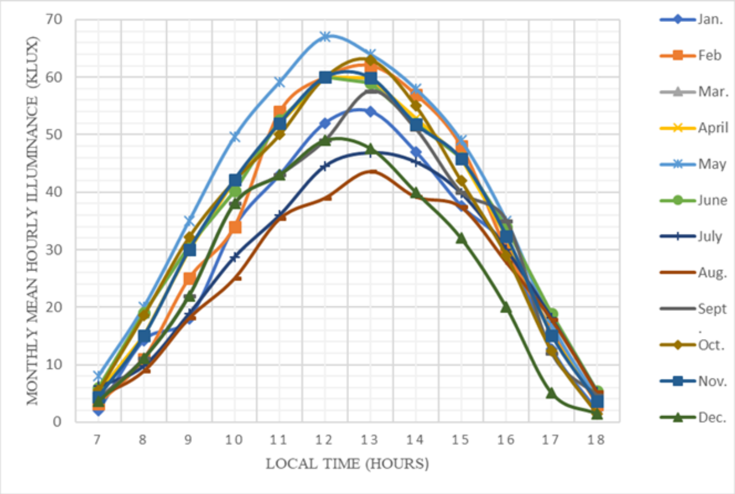

Figure 7: Monthly Mean Hourly Illuminance In Makurdi, Benue State-Nigeria

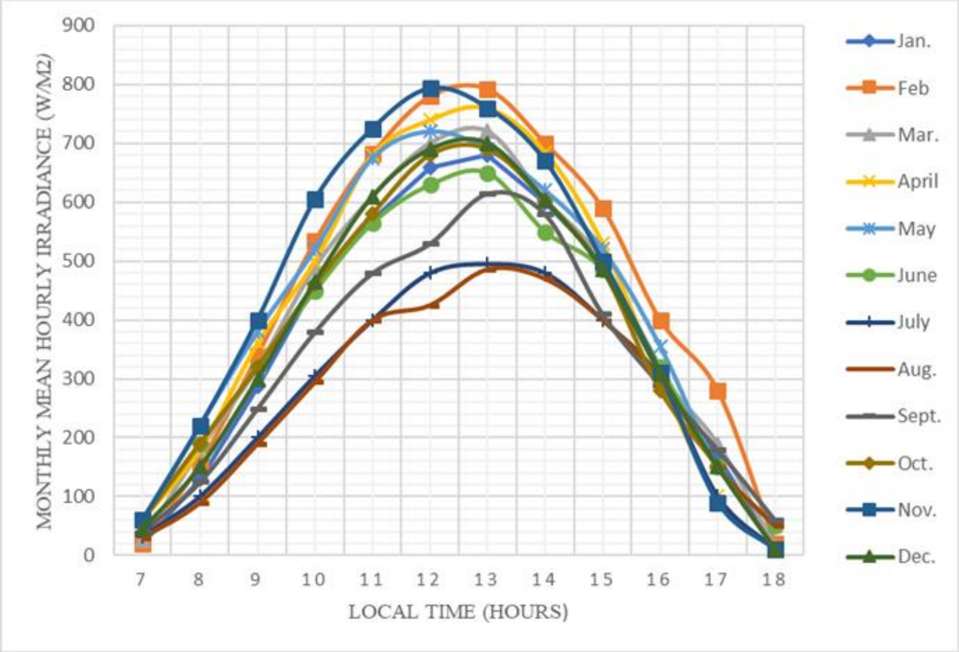

Figure 8: Mean Hourly Irradiance In Makurdi, Benue State-Nigeria

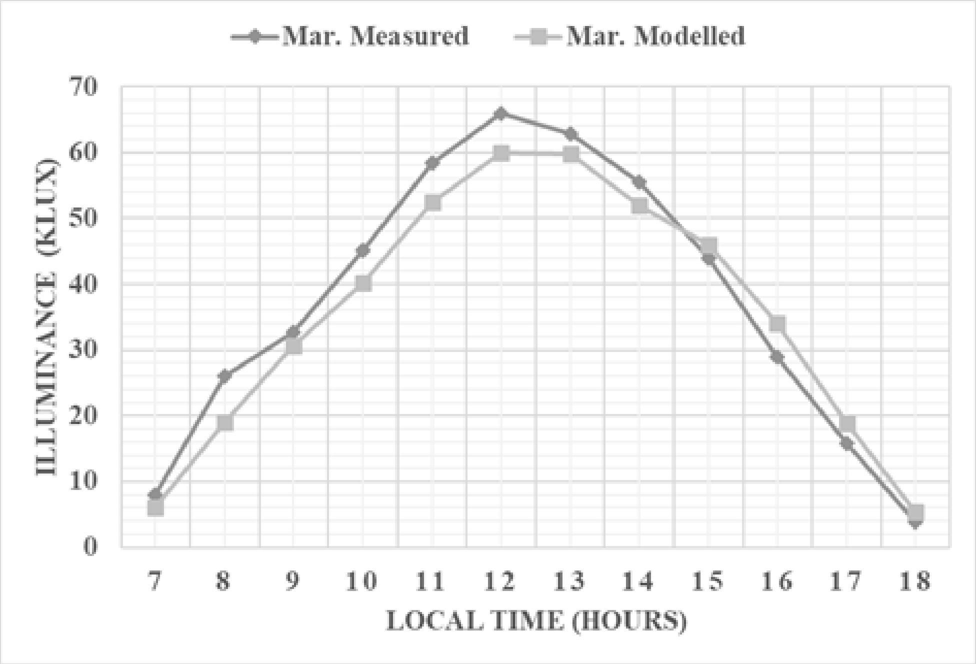

Figure 9: Mean Hourly Modelled and Measured Illuminance in Makurdi, Benue State-Nigeria

The plotted illumination against irradiation for Makurdi-Nigeria (Figure 9) has confirmed the linear progression relationship between solar illumination and irradiation. However, cloud cover measurements, diffuse irradiance, and illuminance based on long-term data are desirable towards this model confirmation.

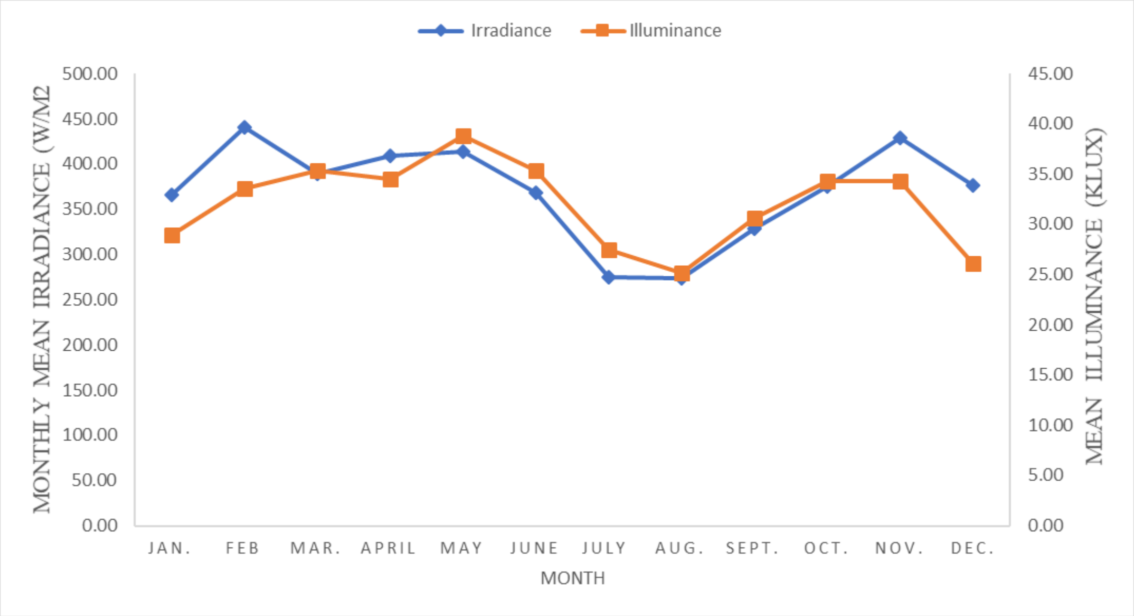

Figure 10: Mean Monthly Irradiance and Illuminance in Makurdi, Nigeria

The comparative analysis has shown a strong correlation in the pattern, as shown in Figure 10. Although the numeric values were not the same, however, the daylight ratio equation can be applied to obtain the estimated indoor illuminance as used in (Ayoosu, Lim, and Leng, 2020;

Lim and Heng, 2016). The mean modelled illuminance seems more accurate for generalisation because it is based on long term data input and is not point specific like in the case of measured illuminance. More so, as shown in Table 1, the Pearson correlation revealed the percentage of mutual relationship for the modelled outdoor illuminance, measured outdoor illuminance, and simulated outdoor illuminance for 0900, 1200, and1500 hours at 100.0%, 95.6% and 84.8%; 95.6%, 100.0%, and 67.2; and 84.8%, 67.2%, and 100.0% respectively.

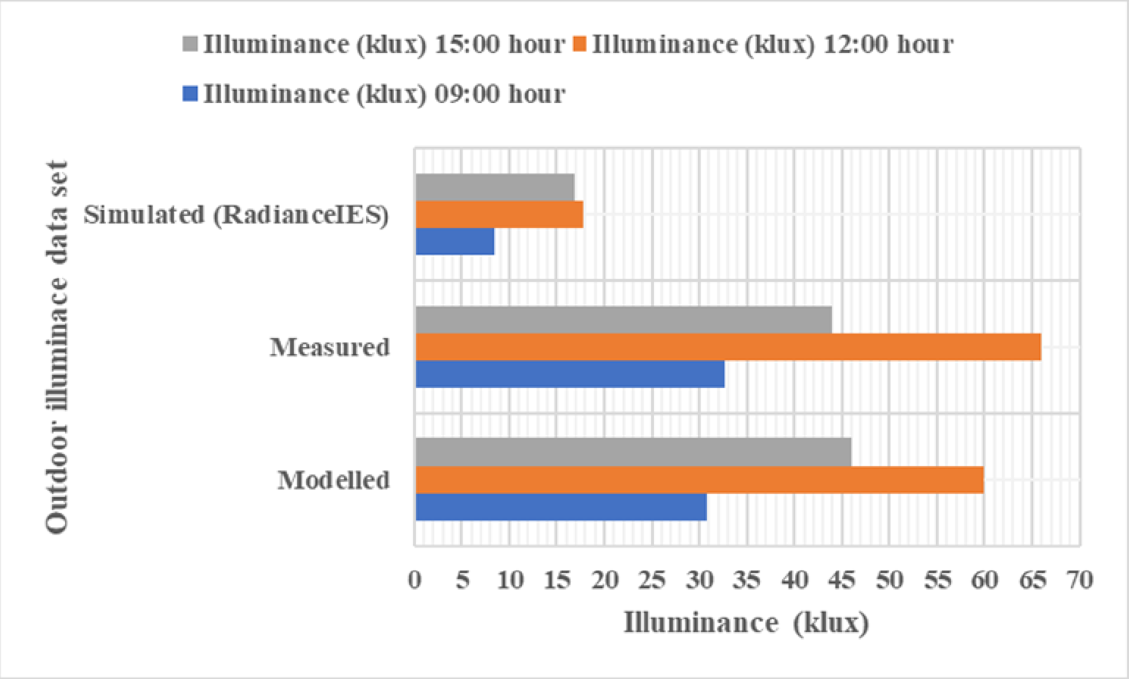

Figure 11: Comparative Mean Outdoor Illuminance In Makurdi, Nigeria

Table 1: Correlations of Outdoor Illuminance

		Modelled Outdoor illuminance	Measured Outdoor illuminance	Simulated Outdoor illuminance
Modelled	Pearson Correlation	1	.978	.921
	Sig. (2-tailed)		.133	.255
	N	3	3	3
Measured	Pearson Correlation	.978	1	.820
	Sig. (2-tailed)	.133		.388
	N	3	3	3
Simulated	Pearson Correlation	.921	.820	1
	Sig. (2-tailed)	.255	.388	
	N	3	3	3

Conclusion

The sky in Nigeria is mostly intermediate; this means that the sky is not overcast or clear. The values of efficacies of the direct, diffuse, and global illumination components were calculated employing the nine years of data as input collected from the meteorological station in Makurdi to evaluate the horizontal surface illumination. The standardised values of 115 lm/W and 144 lm/W are established for overcast and clear skies, respectively. This study deducts efficacies values for global, direct, and diffuse components; 122, 105, and 117 lm/ W were deduced, respectively. The luminous diffuse efficacy values are between the conventional values of 115 and 144lm/W. On the field, the hourly illumination values were modelled using efficacy values. The findings are, the illumination might get up to approximately 80,000 lux through the peak months, and during the cloudy months, it may reach 45,000 lux. The study also concluded that the mean outdoor illuminance for design is 30.7klux, 60.0klux, and 46.0klux at 0900, 1200, and1500 hours, respectively. This study is limited daylight availability and sky types in the tropical climate of Makurdi-Nigeria with the data years. For adequate precision in the data, photometric luminance measurements and ground illuminance on a long-term basis are required for further investigation.

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