Short-term Solar Irradiance Evaluation and Modeling of a Hybrid Distribution Generation System for a Typical Nigeria University

Conference Paper · October 2020

DOI: 10.1109/PowerAfrica49420.2020.9219809

2020 IEEE PES/IAS PowerAfrica

Short-term Solar Irradiance Evaluation and Modeling of a Hybrid Distribution Generation System for a Typical Nigeria University

Oladimeji Joseph Ayamolowo
Dept. of Electrical, Electronics and Computer Engineering
Afe Babalola University
Ado-Ekiti, Nigeria
ayamolowooj@abuad.edu.ng

Samson Olasunkanmi Adigun
Dept. of Electrical, Electronics and Computer Engineering
Afe Babalola University
Ado-Ekiti, Nigeria
adigunso@abuad.edu.ng

Patrick T. Manditereza
Dept. of Electrical, Electronics and Computer Engineering
Central University of Technology
Free State, South Africa
pmandite@cut.ac.za

***Abstract*—Intermittency of renewable energy sources is of great concern to Researchers. For example, PV panels are limited due to the variability of solar irradiances. To further integrate PV into the overall energy mix, accurate assessment and evaluation of its performance is important. This paper aims to evaluate the potential and variability of solar energy at Afe Babalola University, also the possibility of incorporating PV system into the energy mix in ABUAD is investigated. To this end, measurements of solar irradiance (GHI) are collated from January 2018 to December 2018 using the Tenmars TM 206 Pyranometer. In addition, a hybrid system was modeled using HOMER, which gives an optimal system comprising of 1800kW PV panels, 1500kW diesel generator, 1200kW converter and four Trojan T-105 batteries with the levelized cost of energy (COE) of 0.719$/yr and Net Present Cost (NPC) of $41,676,188.**

***Index Terms*-- Renewable energy, Global horizontal irradiance (GHI), temperature, HOMER, Pyranometer.**

I. INTRODUCTION

Presently, Nigeria is plaque with serious power generation challenge as the country power generation still oscillates between 4000MW and 5000MW,for its over 180 million populace[1]. More so, over 70% of this population are not connected to the national grid, despite efforts made by various administrators[1]–[5].

On the other hand, Nigeria is blessed with several renewable energy sources , having an average daily solar radiation of about 5.2kWh/m^2/day and 4.0 to 9.0 hours of sunshine per day depending on location and seasonal differences [6]. This calls for an urgent intervention by way of complementing its present available power generation using renewable energy sources.

All over the world, increasing human activities and desire for clean energy has further increased penchant for renewable energy sources as a means of providing sustainable power for domestic and industrial activities. To this end, solar energy is one of the most abundant renewable source, with the Sun emitting about 63MW of power for every meter square (m^2) of its surface, which amounts to approximately $3.720*10^{20}$ MW globally.

Furthermore, the study of solar irradiance variability is important before installation of PV plant at any given location because the output of PV panel is proportional to the amount of solar irradiance incident on the PV panel [7]. Therefore, accurate feasibility study of solar irradiance will help in predicting the potential of PV plant, while also giving accurate assessment of solar panel operating characteristics thus aiding technological research and development.

Solar radiation can also be estimated using some meteorological parameters such as temperature and cloud cover [8], [9]. In essence, according to [7], solar irradiance is positively correlated with temperature, weather types and wind speed but negatively correlated with humidity and dew point.

Several researchers in a bid to estimate solar irradiance had developed different models using available data from meteorological stations. For example, the Angstrom-Prescott and Hargreaves-based model uses the sunshine duration and extraterrestrial irradiance value to estimate the global irradiance [10], while others use deep learning approach. More so, the authors in [11] forecasted solar irradiance using five machine learning technique such as FoBa, leapForward, spikeslab, Cubist and bagEarthGCV models. This model was validated using the correlation coefficient (CC) and root mean square error (RMSE), with spikeslab and Cubist model outperforming the others.

In this paper, the second section gives an introduction to measurement of solar radiation. The third section, deals with global horizontal irradiance (GHI) data collection techniques and validation of GHI dataset from the Pyranometer. Modeling, simulation, and assessment of the proposed hybrid PV/Diesel power system are covered in section IV, while section V, and section VI gives the discussion and conclusion of the paper respectively.

II. GLOBAL HORIZONTAL IRRADIANCE (GHI) EVALUATION

Solar radiation is the instantaneous power density in watts per square metre (W/m^2) incident on the PV panel, while, GHI is the sum of the direct, diffuse and reflected solar radiations received by earth's surface. GHI can be estimated from data of DNI and DHI as represented in equation (1). GHI are the best source of information for estimating the productivity of an installed PV system, while, Direct Normal Irradiance (DNI) is required in applications such as solar thermal energy systems or concentrated solar systems [12].

$$GHI = DNI \cos\theta + DHI \tag{1}$$

where , θ is the solar zenith angle (SZA), DHI is the Diffuse Horizontal Irradiance (DHI) and DNI is the Direct Normal Irradiance. Fig. 1 shows the solar irradiance incident on the PV panel at an angle, ϴ to the normal plain.

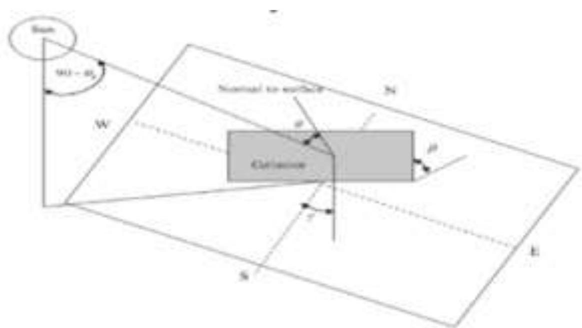

Fig. 1. Solar irradiance on PV panels [13].

Daily total GHI can also be evaluated on a clear day from equation 2, as defined by the Hargreaves Samani model which estimates GHI values from recorded data of sunshine hours.

$$GHI = K_{RS} * I_o * \sqrt{T\max - T\min} \tag{2}$$

Where, Tmax is the maximum temperature (^{o}C), Tmin is the minimum temperature(^{o}C), I_o is the extraterrestrial solar radiation (MJ/m^2/day) and K_{RS} is the adjustment coefficient ranging from 0.16 to 0.19 depending on the site.

A. Measuring and Modeling Solar Radiation

Solar resource data can be generally obtained from satellite based models and, highly accurate solar sensors mounted at specific meteorological stations or from satellite imagery.

Dataset obtained from sensors have higher reliability and accuracy, but it is limited by its coverage. On the other hand, satellite imagery based model are cost effective and cover a larger geographical area, housing a large database (up to 10years dataset), however, these models are limited by spatial resolution, lower accuracy and high uncertainty. Satellite imagery based model are therefore used to validate the quality of data obtained by ground meteorological sensors.

B. GHI Evaluation Using the Pyranometer

The Pyranometer is a specialized radiometer which offers an inexpensive but reliable means of obtaining real-time global horizontal irradiance data on the horizontal surface. It operates for wavelength band between 300 nanometers (nm) to 2800nm by simply converting the incident radiation from the sun to heat, thereby establishing a temperature difference between the surface and the body of the instrument. This temperature gradient is recorded by a thermopile and being proportional to the solar irradiance, is used to establish the solar irradiance readings. The advantage of the Pyranometer is the provision of real-time hourly GHI dataset.

C. Solar Irradiance Evaluation Using the Global Solar Atlas

The World Bank in collaboration with Solaris has provided the Global Solar Atlas in a bid to aid solar power project around the World by providing long-term daily dataset which is used in estimating the PV solar potential in a given geographical location. The Atlas spans region within latitude 60^{o}N to 45^{o}S, with dataset being powered from three satellite providers, namely the EUMETSAT & Japanese Meteorological Agency, National Oceanic and Atmospheric Administration. Fig. 2 shows the solar resource map for Nigeria as provided by Global Solar Atlas.

Fig. 2. Global horizontal irradiation map for Nigeria powered by Global Solar Atlas.

III. METHODOLOGY

In general, solar irradiance is an important parameter used in the studies of solar systems. It provides useful information on solar resources, which is used to determine the amount of energy that can be harnessed from the sun. In this section, GHI dataset are obtained for Afe Babalola University from January to December, 2018.

A. Area of Study

Afe Babalola University is a private University located in south-western part of Nigeria, Ado-Ekiti, which is the capital of Ekiti state. Afe Babalola University lies between latitude 7.6110^{o}N and longitude 5.2571^{o}E, occupying a surface area of about thirteen (13) square kilometers at an elevation of 382 metres above sea level (a.s.l). The campus has an average temperature of 24.7^{o}C, with about ten hours of daily sunshine. Two seasons are prevalent in Nigeria, the rainy season and the dry season. The dry season spans from November to February, while raining season from March to

October. The campus promises to have an excellent potential for solar resources.

B. Load Profile of ABUAD

Fig. 3 shows the hourly load distribution for the campus during the research. A base load of 120kW was observed between 1 am and 4 am, while the load begins to increase substantially from 8am and then attains its peak load of 1451kW at 2pm. A further decline is observed from 2pm to 5pm, though it again increased from 6pm-9pm. Furthermore, daily peak load of the study area is obtained as 1541kW, while the average energy consumed is given as 12MWh/day.

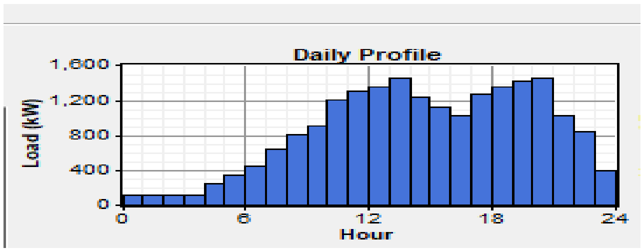

Fig. 3. The daily load profile of ABUAD.

C. Pyranometer Measurement and Data Collection

Accurate and real-time measurement of GHI were obtained using the Tenmars TM 206 Pyranometer, which has a maximum measuring range of 2000W/m^2. Hourly GHI measurements were obtained from January to December 2018, between 8.00 am and 6pm. Fig. 4 gives the pictorial view of Tenmars TM-206 solar power radiation meter that was used for solar irradiance measurement ,while Table I shows a sample of the GHI readings as obtained using the Tenmas TM 206 pyranometer at Afe Babalola University campus.

Fig. 4. Tenmars TM-206 Pyranometer.

TABLE I. HOURLY GHI READINGS FROM TENMARS TM 206 PYRANOMETER.

Time of the day	**Global Horizontal irradiance (GHI) w/m^2**	**Temperature(ºC)**
8.00	106.7	23
9.00	199.8	24
10.00	254.6	25
11.00	398.2	27
12.00	898.3	28
13.00	1020.9	28
14.00	801.5	29
15.00	417	29
16.00	393	28
17.00	150.2	28
18.00	116.5	26
Average	432.4273	26.81818

D. Global Solar Atlas GHI Measurement

Given the coordinates of any given area the GLOBAL SOLAR ATLAS can be used to obtain its corresponding solar irradiance dataset. Fig. 5 shows GHI readings as obtained from the Global Solar Atlas, while, Table II gives a sumarised dataset from the Global Solar Atlas.

Fig. 5. Global Solar Atlas GHI data.

TABLE II. SUMMARISED RESULT FROM GLOBAL SOLAR ATLAS.

Average Temp. T (ºC)	24.7
GHI Annual Average (kwh/m^2)	1784
GHI Daily Average (kWh/m^2)	4.888
DHI Annual Average (kwh/m^2)	1067
DHI Daily average (kWh/m2)	2.923
DNI Annual Average (kWh/m^2)	941
DNI Daily Average (kWh/m^2)	2.578

E. Homer System Implementation

HOMER is an acronym for Hybrid Optimization Model for Electric Renewable (HOMER), it was developed by National Renewable Energy Laboratory, in the United States. HOMER has also been licensed to obtain solar irradiance and wind speed data from the solar energy website of the National Aeronautics and Space Administration (NASA), this information is important to this study.

Furthermore, HOMER can also be used to design a hybrid system for off-grid and on-grid application. This system can then be optimized and critically evaluated to obtain the best hybrid configuration suited for operation.

F. Global Horizontal Irradiance (GHI) Data Collection from NASA

The coordinates (latitude and longitude) of the study area are used to extract the solar irradiance data and the corresponding clearness index from NASA. Table III gives the comprehensive daily average GHI values from January to December 2018, with their associated clearness index.

It is observed that the GHI values ranged from 4.100kWh/m^2/day to 5.734kWh/m^2/day, while the clearness index ranged from 0.404 to 0.620. Also, the annual average GHI was given as 5.119kWh/m^2/day and the average clearness index is given as 0. 517. Table III and fig. 6 gives the daily mean GHI dataset for the months in 2018 with their corresponding clearness index.

TABLE III. MONTHLY GLOBAL HORIZONTAL IRRADIANCE (GHI) AND CORRESPONDING CLEARNESS INDEX.

Month	**Clearness Index**	**Daily average GHI(kWh/m^2/d)**
January	0.582	5.320
February	0.566	5.517
March	0.551	5.685
April	0.545	5.715
May	0.505	5.193
June	0.466	4.708
July	0.404	4.100
August	0.409	4.230
September	0.451	4.648
October	0.527	5.204
November	0.620	5.734
December	0.609	5.427
Average	0.517	5.119

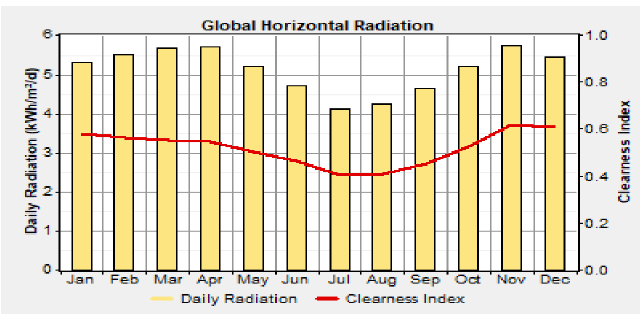

Fig. 6. Monthly average solar irradiance and clearness index.

IV. MODELING OF A HYBRID SYSTEM USING HOMER

The modeling of a hybrid, PV/diesel power system was carried out using HOMER. The financial implication of incorporating PV into the energy mix was also closely observed. System equipment and their ratings used in the modeling of the hybrid, PV/diesel power system are represented in Table IV. Table IV also gives further information on the size, model, cost (capital, replacement and running), expected lifetime, derating factor, efficiency e.t.c of the proposed system. In order to obtain a workable model, the ideal prices of system equipment were obtained from Rubitec Nigeria limited, which is a solar energy company located in Lagos, Nigeria.

TABLE IV. SPECIFICATION OF SYSTEM COMPONENTS USED IN THE HOMER DESIGN.

COMPONENTS		**SPECIFICATIONS**
PV PANEL	Size	0-1800kW
	Capital ($)	946 per kW
	Replacement ($)	756 per kW
	O&M Cost ($/yr)	0.00
	Life time	20 years
	Derating	0.70
ABUAD Diesel Generation	Size	0-1800kW
	Capital($)	300
	Replacement ($)	270
	O&M Cost ($/hr)	0.023
	Life time (hours)	15,000
	Fuel	diesel
	Fuel price/litre ($)	0.58
Inverter	Size	0-1800kW
	Capital($)	300
	Replacement ($)	300
	O&M Cost ($/yr)	0
	Life time (years)	20
	Efficiency (%)	90
Battery	Model	Trojan T-105
	Capital($)	1100
	Replacement ($)	1100
	O&M Cost ($/yr)	0
	Nominal Capacity	225Ah
	Nominal Voltage	6V
	Life time(years)	10
	Lifetime throughput(kWh)	845
	Battery per string	2
	State of charge	30%

A. Modeling of the Hybrid Power System

Here, a hybrid PV/diesel power system was designed using HOMER, with system components comprising of the diesel generator, PV panel, converter, and battery. The PV power system will supplement the power from the diesel generator, with the aid of the converter. The battery bank will therefore act as an energy storage system, as it will be brought into operation during system emergencies, while it is being constantly charged at other times by the excess electricity produced by the PV system. Fig. 7 shows the schematic diagram of the proposed hybrid PV/diesel power system for the University campus.

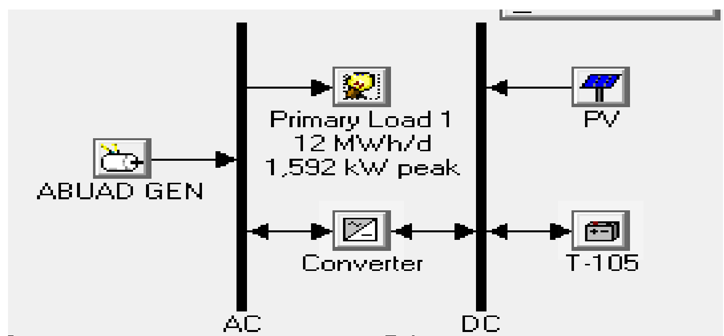

Fig. 7. Schematic diagram of a hybrid power system for ABUAD.

V. RESULTS AND DISCUSSIONS

In this section, critical analysis of the proposed hybrid power system for ABUAD as modeled in HOMER, will be discussed.

A. Simulation Result of the Modeled Hybrid Power System

Simulations performed by HOMER software compared 1176 different system configuration considering the inputted variables, in order to obtain the most cost efficient and reliable system combination. The result showed an optimal system comprising of 1800kW PV,1500kW diesel generator, 1200kW converter with four T-105 battery having the levelized cost of energy(COE) of $0.719 $/yr, Net Present Cost (NPC) of $41,676,188 and operating cost of $3,063,279. Furthermore, Table V gives a comprehensive analysis of the internal component of the Net Present Cost (NPC) and further reveals that though the 1500KW diesel generator had the lowest levelized initial installation cost. Conversely, it has the highest cost of operation and maintenance. Also, the 1800 PV power plant has the highest cost of installation and a negligible running cost.

TABLE V. COST DETAILS OF DIFFERENT SYSTEM COMPONENT.

Component	Capital($)	Replacement($)	O&M($)	Fuel($)	Salvage($)	Total ($)
PV	1,702,800	424,304	0	0	-237,799	1,889,306
ABUAD GEN	450,000	2,667,234	3,543,203	32,766,968	-57,563	39,369,840
Trojan T-105	4,400	3,829	0	0	-513	7,716
Converter	360,000	112,250	0	0	-62,910	409,340
System	2,517,200	3,207,617	3,543,203	32,766,968	-358,784	41,676,200

B. Environmental Assessment of the Modeled Hybrid System

Considering the increasing damaging effect of greenhouse gases emissions (GHGs) on the ecosystem. A critical environmental assessment will be important to ascertain the degree of ecosystem friendliness of the proposed hybrid system. Table VI reveals the amount of green house gases (GHGs) emitted by the proposed hybrid model as compared with that of the standalone diesel power System. The results clearly shows that the amount of pollutant was greatly reduced by sixteen percent. This further shows that the proposed hybrid system is more ecosystem friendly that the conventional standalone diesel generator, because of its reduced dependance on fossil fuel.

TABLE VI. GREEN HOUSE GASES EMISSIONS(GHGs).

Pollutant	GHGs emissions (Kg/yr.)	
	Types of System	
	PV/Diesel	Diesel Standalone
Carbon dioxide	5,357,051	6,376,158
Carbon monoxide	13,223	15,739
Unburned hydrocarbons	1,465	1,743
Particulate matter	997	1,186
Sulfur dioxide	10,758	12,804
Nitrogen oxide	117,991	140,437
Total	5,501,485	6,548,067

VI. CONCLUSION

In this study, the global horizontal irradiance was obtained from January 2018 to December 2018 using the Tenmars TM 206 Pyranometer at Afe Babalola University. The minimum and maximum daily GHI obtained from the test site was 4.100kWh/m^2/day and 5.734kWh/m^2/day respectively, while the mean daily global horizontal irradiance was 5.12kWh/m^2/day. Furthermore, the higher values of GHI was obtained during the dry season (November to March) between the hours of 12 pm to 2 pm.

In addition, the financial impact of incorporating PV system into the energy mix of Afe Babalola University was investigated. A hybrid PV/diesel power system was modeled and simulated using HOMER. The results gave an optimized system configuration comprising of 1800 kW PV, 1500kW diesel generator, 1200kW converter and four Trojan T-105 batteries. This suggests that 600W from the PV system will be used to charge the T-105 batteries, however, when the batteries are full, the PV plant will be made to operate on deloading mode.

The proposed hybridized system has cost of energy (COE) of 0.719$/yr, Net Present Cost (NPC) of $41,676,188 and an operating cost of $3,063,279. Thus, this hybrid system will help improve the overall power reliability of Afe Babalola University, as continued power supply is ensured with the aid of the battery bank.

Finally, the GHGs emission is reduced by sixteen percent in the proposed hybrid system, which is equivalent to 1047 tons of GHGs. This further affirms that the proposed hybridized power system is a better choice for the electrification of Afe Babalola University campus.

REFERENCES

[1] O. J. Ayamolowo, O. Folorunso, and E. Buraimoh, "Fault Analysis of Injection Substation Using Symmetrical Component Method A Case Study of Mofor Injection Substation , Delta State Nigeria .," *Am. J. Eng. Res. (AJER),* vol. 6, no. 10, pp. 83–97, 2017.

[2] O. J. Ayamolowo, A. O. Salau, and S. T. Wara, "The Power Industry Reform in Nigeria : The Journey So Far," *2019 IEEE PES / IAS Power Africa,Abuja,Nigeria,, 2019*, pp. 12–17.

[3] O. J. Ayamolowo, E. Buraimoh, A. O. Salau and J. O. Dada, "Nigeria Electricity Power Supply System : The Past , Present and the Future," *2019 IEEE PES/IAS PowerAfrica, Abuja, Nigeria,* 2019, pp. 64-69.

[4] O. J. Ayamolowo, C.A Mmonyi, S.O Adigun, O.A Onifade, K.A Adeniji, and A. S Adebanjo, "Reliability Analysis of Power Distribution System : A Case Study of Mofor Injection Substation , Delta." *2019 IEEE Africon,Accra,Ghana, 2019,* pp. 66-71

[5] O. J. Ayamolowo, A. O. Ajibade, A. O. Salau, A. J. Akinwumi, C. A. Mmonyi, and O. A. Onifade, "Energy Audit and Reliability Analysis of Power Distribution System : A Case Study of Afe Babalola."*2019 IEEE Africon, ,Accra,Ghana,, 2019* pp. 45-51

[6] T. T. Onifade, "Renewable Energy In Nigeria : A Peep Into Science , A Conclusion On Policy," *Int. jounal Innov. Sci. Technol.*, vol. 1, no. June, 2016.

[7] X. Qing and Y. Niu, "Hourly day-ahead solar irradiance prediction using weather forecasts by LSTM," *Energy*, vol. 148, pp. 461–468, 2018.

[8] S. D. Miller, M. A. Rogers, J. M. Haynes, M. Sengupta, and A. K. Heidinger, "Short-term solar irradiance forecasting via satellite / model coupling," *Sol. Energy*, no. November, pp. 0–1, 2017.

[9] J. Ballestrín, M. Casanova, R. Monterreal, J. Fernández-Reche, E. Setien, J. Rodríguez, J. Galindo, F.J. Barbero, F.J. Batlles, "Simplifying the measurement of high solar irradiance on receivers. Application to solar tower plants," *Renew. Energy*, 2019.

[10] T. A. Otunla, "Estimates of clear-sky solar irradiances over Nigeria," *Renew. Energy*, 2018.

[11] A. Sharma and A. Kakkar, "Forecasting daily global solar irradiance generation using machine learning," *Renew. Sustain. Energy Rev.*, no. May, pp. 0–1, 2017.

[12] V. Srikrishnan, G. S. Young, L. T. Witmer, and J. R. S. Brownson, " Using multi-pyranometer arrays and neural networks to estimate direct normal irradiance," *Sol. ENERGY*, vol. 119, pp. 531–542, 2015.

[13] M. A. Danandeh and S. M. G. Mousavi, "Solar irradiance estimation models and optimum tilt angle approaches : A comparative study," *Renew. Sustain. Energy Rev.*, vol. 92, no. May 2017, pp. 319–330, 2018.