Techno-Economic Viability Assessment of Standalone Solar PV System for Rural Electric Power Supply

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ABSTRACT: The techno-economic analysis emphasizing on energy production and cost of energy from photovoltaic stand-alone system at Umudike in eastern Nigeria was analyzed in this paper. This was carried out by obtaining data on the daily energy consumption of umudike, excess electricity and unmet electric load. The annual average solar irradiation considered in this study was obtained as 4.71kWh/m^2/day. Hybrid Optimization of Multiple Energy Resources software was used to perform the technical and economic analysis of the stand-alone system in Umudike to ensure generation of uninterrupted power supply and to meet its energy demands, a photovoltaic system of 78.2 kW should be installed at a net present cost of $442,683 and an initial capital cost of $330,211. The photovoltaic stand-alone system will help to proffer solution to the daily power outages lasting several hours in Umudike. The photovoltaic Standalone System is a good source of continuous power generation, as it reduces combustion of fossil fuels and the consequent carbon dioxide emission which is the main cause of greenhouse-effect and global warming.

Keywords: Techno-economic, Energy, Photovoltaic (PV) Stand-alone, Power Supply, Umudike

Electricity can be put to a vast set of applications which include transport, heating, lighting, communication and computation to mention a few. Electric power is important to the industrial society as well as the educational sector. The tertiary institutions also use electricity to a great deal, as it (electricity) aids learning and research. Developed as well as developing countries have ventured into researches and applications of renewable sources of energy. The renewable energy is aimed at reducing carbon emission from energy generation and improving the reliability of energy supply. (El-Shafy, 2009). Global concerns about climate change, energy security, exhaustion of fossil resources and its impact on the society have become important consideration for policy and decision makers (El-Rafey and El-Sherbiny 1998). The photovoltaic (PV) stand-alone system is environmentally friendly, noiseless and available in abundance especially in Umudike. A PV deals with the conversion of light into electricity using semi-conducting materials that exhibit the photovoltaic effect (Carolyn, 2009). A photovoltaic system is a power system designed to supply usable solar power by means of photovoltaics. (Bagul, 1996). The electricity supply to Umudike is characterized by inconsistent power outage lasting for several hours which in turn affects the general activities of the community. To proffer solution to this, the techno-economics viability of the system was carried out, the energy consumption of the department was determined, taking in consideration various appliances and equipment used in the community. Therefore, it is imperative to produce reliable and consistent power supply to the community at an optimal cost.The techno-economic and environmental analysis of PV stand-alone system for, Umudike, Nigeria (Latitude: 5°28'7", Longitude: 7°32'6") located about 10 kilometers from Umuahia, the Abia State capital. Umudike is rich with solar irradiance which makes solar energy a viable source of energy. Technical as well as economic analysis were conducted for photovoltaic system with battery storages and a controller system. HOMER was used as the tool that facilitated the optimum design of the photovoltaic system. This simulation involves data on capital expenses, operation and maintenance as well as

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replacement costs (Chiemeka and Chineke 2009). For the simulation of the PV stand-alone system, the key variables to be examined are PV array, battery capacity to help determine the optimum PV stand-alone energy configuration that is the optimal based on energy cost, energy production, excess electric load and unmet electric load (Bhagwan . and Reddy. 2008). Furthermore, the investigation places much emphasis on energy production, served and unserved electricity demand and cost of energy.

MATERIALS AND METHODS

This research was carried out within Umudike and the specified area of interest being Mechanical Engineering Department of Michael Okpara University of Agriculture Umudike (MOUAU), Nigeria at the location of latitude of 5°28'7" and longitude: 7°32'6". The PV array used in the simulation is a generic flat plate with 1kW capacity, derating factor 80% and 25-year lifetime.
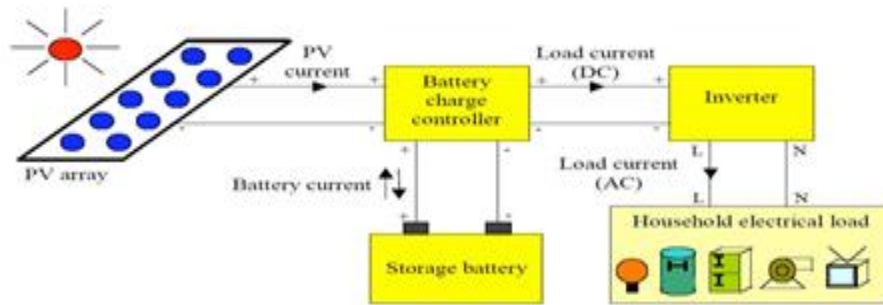

Fig.1. Major Component of photovoltaic stand-alone system

Fig 1 contains the illustration of the system, which is the energy flow diagram of the system. It shows how the energy is transferred from the Sun to the PV array, then to the load for final use with the help of the arrow head. It also shows the battery and the controller. The power output of the PV array is expressed equation (1) to equation (17) by HOMER and (Vaishaelee, et al., 2018)

$$P_{PV} = Y_{PV} f_{PV} \left(\frac{\bar{G}_T}{\bar{G}_{T,STC}} \right) \left[1 + \alpha_P \left(T_C - T_{C,STC} \right) \right] \qquad (1)$$

Where P_{PV} *is* the output power of the PV array, Y_{PV} is The rated capacity of the PV array power output under standard test conditions [Kw], f_{PV} is the PV derating factor [%], $\bar{G}_T$ is the solar radiation incident on the PV array in the current time step [kW/m²], $\bar{G}_{T,STC}$ is the incident radiation at standard test conditions [1 kW/m²], α_P is the temperature coefficient of power [%/°C], T_C is the PV cell temperature in the current time step [°C] and $T_{C,STC}$ is the PV cell temperature under standard test conditions [25°C]. For temperature it is expressed using equation (2)

$$T_c = T_a + G_T \left(\frac{\tau\alpha}{U_L} \right) \left(1 - \frac{n_c}{\tau\alpha} \right) \qquad (2)$$

Where T_c is the PV cell temperature [°C], τ is the solar transmittance of any cover over the PV array [%], α is the solar absorptance of the PV array [%], G_T is the solar radiation striking the PV array [kW/m²], η_c is the electrical conversion efficiency of the PV array [%], U_L is the coefficient of heat transfer to the surroundings [kW/m²°C], and T_a is the ambient temperature [°C]. It is usually very hard to measure the value of ($\tau\alpha / U_L$) directly, so instead the nominal

operating cell temperature (NOCT), which is defined as the cell temperature that results at an incident radiation of 0.8 kW/m², an ambient temperature of 20°C, and no load operation (meaning $\eta_c = 0$). We can then substitute these values into the equation 2 above and solve it for $\tau\alpha / U_L$ to yield equation 3.

$$\frac{\tau\alpha}{U_L} = \frac{T_{c,NOCT} - T_{a,NOCT}}{G_{T,NOCT}} \qquad (3)$$

where $T_{c,NOCT}$ is the nominal operating cell temperature [°C], $T_{a,NOCT}$ is the ambient temperature at which the NOCT is defined [20°C] and $G_{T,NOCT}$ is the solar radiation at which the NOCT is defined [0.8 kW/m²] . If we assume that $\tau\alpha/U_L$ is constant, substitute this equation into equation 2 to get

$$T_c = T_a + G_T \left(\frac{T_{c,NOCT} - T_{a,NOCT}}{G_{T,NOCT}} \right) \left(1 - \frac{n_c}{\tau\alpha} \right) \qquad (4)$$

Assuming a value of 0.9 for $\tau\alpha$ in the equation above, as Duffie and Beckman (1991) suggest. Because the term $\eta_c/\tau\alpha$ is small compared to unity, this assumption does not introduce significant error. HOMER assumes that the PV array always operates at its maximum power point, as it does so when controlled by a

maximum power point tracker. That means HOMER assumes the cell efficiency is always equal to the maximum power point efficiency.

$$n_c = n_{mp} \qquad (5)$$

Where η_{mp} is the efficiency of the PV array at its maximum power point [%].

So in the equation 4 for cell temperature, we can replace η_c with η_{mp} to yield

$$T_c = T_a + G_T \left(\frac{T_{c,NOCT} - T_{a,NOCT}}{G_{T,NOCT}}\right)\left(1 - \frac{n_{mp}}{\tau\alpha}\right) \quad (6)$$

The orientation of the PV array using two parameters: a slope and an azimuth. The slope is the angle formed between the surface of the panel and the horizontal, so slope of zero indicates a horizontal orientation, whereas a 90° slope indicates a vertical orientation. The azimuth is the direction towards which the surface faces. Using the convention whereby zero azimuth corresponds to due south, and positive values refer to west-facing orientations. So an azimuth of -45° corresponds to a southeast-facing orientation, and an azimuth of 90° corresponds to a west-facing orientation. Other factors which are relevant to the geometry are the latitude includes the time of day and the time of year. The time of year affects the solar declination, which is the latitude at which the sun's rays are perpendicular to the earth's surface at solar noon. Using the equation 9 to calculate the solar declination:

$$\delta = 23.45^o \, sin\left(360^o \, \frac{284+n}{365}\right) \qquad (9)$$

Where *n is* the day of the year [a number 1 through 365].

The time of day affects the location of the sun in the sky, which we can describe by an hour angle. Using the convention whereby the hour angle is zero at solar noon (the time of day at which the sun is at its highest point in the sky), which is negative before solar noon, and positive after solar noon. Using the equation 10 to calculate the hour angle:

$$w = (t_s - 12hr).15^o/hr \qquad (10)$$

But η_{mp} depends on the cell temperature T_c. HOMER assumes that the efficiency varies linearly with temperature according to equation 7.

$$n_{mp} = n_{mp,STC}\left[1 + \alpha_P\left(T_c - T_{c,STC}\right)\right] \qquad (7)$$

Where $\eta_{mp,STC}$ is the maximum power point efficiency under standard test conditions [%], α_P is the temperature coefficient of power [%/°C] and $T_{c,STC}$ is the cell temperature under standard test conditions [25°C]. The temperature coefficient of power is normally negative; this means that the efficiency of the PV array decreases with increasing cell temperature. We can substitute this efficiency equation into the preceding cell temperature equation and solve for cell temperature to yield:

$$T_c = \frac{T_a + (T_{c,NOCT} - T_{a,NOCT})\left(\frac{G_T}{G_{T,NOCT}}\right)\left[1 - \frac{n_{mp,STC}(1 - \alpha_P T_{c,STC})}{\tau\alpha}\right]}{1 + (T_{c,NOCT} - T_{a,NOCT})\left(\frac{G_T}{G_{T,NOCT}}\right)\left(\frac{\alpha_P n_{mp,STC}}{\tau\alpha}\right)} \qquad (8)$$

Where t_s *is* the solar time [hr]

The value of t_s is 12 hr at solar noon, and 13.5 hr ninety minutes later. The equation above is based on the fact that the sun moves across the sky at 15 degrees per hour. HOMER assumes that all time-dependent data, such as solar radiation data and electric load data, are specified not in solar time, but in civil time (also called local standard time). HOMER calculates solar time from civil time using equation 11.

$$t_s = t_c + \frac{\lambda}{15^o/hr} - Z_c + E \qquad (11)$$

Where t_c *is* the civil time in hours corresponding to the midpoint of the time step [hr], λ *is* the longitude [°], Z_c *is* the time zone in hours east of GMT [hr] *and E is* the equation of time [hr].

Now, for a surface with any orientation, we can define the angle of incidence, meaning the angle between the sun's beam radiation and the normal to the surface, using equation 12.

$$Cos\,\theta = \\ Sin\,\delta\;Sin\,\phi\;Cos\,\beta - Sin\,\delta\;Cos\,\phi\;Sin\,\beta\;Cos\,\gamma\; + \\ Cos\,\delta\;Cos\,\phi\;Cos\,\beta\;Cos\,\omega\; + \\ Cos\,\delta\;Sin\,\phi\;Sin\,\beta\;Cos\,\gamma\;Cos\,\omega\; + \\ Cos\,\delta\;Sin\,\beta\;Sin\,\gamma\;Sin\,\omega \quad (12)$$

Where θ the angle of incidence [°], β is the slope of the surface [°], Φ *is* the latitude [°], δ *is* the solar declination [°] and ω *is* the hour angle [°].

$$R_b = \frac{Cos\,\theta}{Cos\,\theta_z} \tag{13}$$

In equation 13 is R_b is the ratio of beam radiation on the tilted surface to beam radiation on the horizontal surface.

Where θ_z is the ratio of beam radiation on horizontal surface.

The anisotropy index is a measure of the atmospheric transmittance of beam radiation. This factor can be used to evaluate the amount of circumsolar diffuse radiation, also called forward scattered radiation. The anisotropy index is given by equation 14.

$$A_i = \frac{\bar{G}_b}{\bar{G}_o} \tag{14}$$

Where A_i is the anisotropy index, $\bar{G}_b$ is the beam radiation [kW/m^2] and $\bar{G}_o$ is extraterrestrial horizontal radiation average over the time step(kW/m^2).

The global radiation incident on the PV array can be derived from equation 15.

$$\bar{G}_T = (\bar{G}_b + \bar{G}_d A_i)\,R_b + \bar{G}_d(1 - A_i)\left(\frac{1+Cos\,\beta}{2}\right)\left[1 + f\,Sin^3\left(\frac{\beta}{2}\right)\right] + \bar{G}\,P_g\left(\frac{1-Cos\,\beta}{2}\right) \tag{15}$$

Where $\bar{G}$ is the global horizontal radiation on the earth's surface averaged over the time step [kW/m^2], $\bar{G}_T$ is the global radiation incident on the PV array, $\bar{G}_d$ is the diffuse radiation [kW/m^2], β is the slope of the surface [°] and P_g is the ground reflectance. HOMER uses this quantity to calculate the cell temperature and the power output of the PV array. The Schematic diagram of PV standalone system with the HOMER homepage interface and the location of the system is shown in Fig.2.
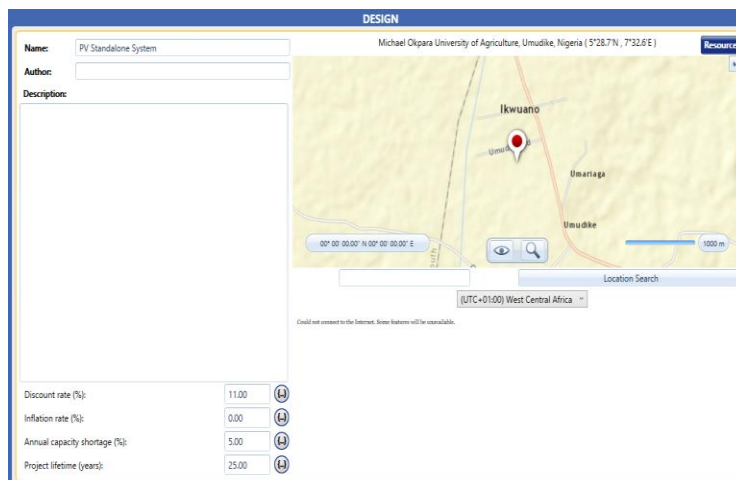

Fig. 2. Schematic diagram of PV standalone system with the HOMER homepage interface and the location of the system.

The economic model for the simulation was developed using net present cost (NPC) which is the total cost of installing and operating the PV standalone system over the lifetime of the system. It models the system by performing an hourly time-step simulation for one year. The total NPC of the system is calculated by equation 16.

$$C_{NPC,tot} = \frac{C_{ann,tot}}{CRF(i,R_{proj})} \tag{16}$$

Where $C_{ann,tot}$ is the total annualized cost ($/yr), i is the annual real interest rate (%), R_{proj} is the project lifetime (yr), and CRF() is a functional returning the capacity recovery factor.

The capital recovery factor (CRF) is given by

$$CRF(i, N) = \frac{i(1+i)^N}{(1+i)^N - 1} \tag{17}$$

Where i is the annual real interest rate and N is the years. It is assumed that all prices escalate at the same rate. HOMER uses an annual real interest rather than a nominal interest rate in the computation. The annual interest rate can be gotten from the nominal interest rate by equation 18.

$$i = \frac{i'-f}{1+f} \tag{18}$$

Where i is the annual real interest rate, i' is the annual nominal interest rate and f is the annual inflation rate

To calculate the cost of energy (COE), divide the annualized cost of producing electricity by the total electric load served, using equation 19.

$$COE = \frac{C_{ann,tot}}{E_{served}} \qquad (19)$$

Where $C_{ann,tot}$ is total annualized cost of the system [$/yr] and E_{served} is total electrical load served [kWh/yr]

Table 1 Electricity production

Quantity	PV array
Rated capacity	1 Kw
Total PV capacity	78.2kW
Total production	108,239kWh/yr

The cost components are critical inputs in the development of energy and COE analysis of a PV standalone system (Henrich, 2017). It also plays a vital role in determining the capacity addition that will serve the electricity demand. The cost components include the capital, replacement then operation and maintenance costs. The PV standalone system has high initial cost but very small operation and maintenance cost due to no fuel expenses. The PV stand-alone system costs are the costs components of the PV array, battery, inverter, controller, wire and other protective equipment. The average price of the PV system including the installation cost is set at $2,500/kW. The operation and maintenance (O&M) cost is derived to be $8/yr. The O&M cost of the PV system may include periodic array water washing and tilt angle adjustment.

Table 2: PV data

PV array	Quantity
Lifetime	25 years
Cost of investment	$2500/kW
Cost of O&M	$8/yr
Cost of replacement	$2,500/kW

RESULTS AND DISCUSSION

The results obtained analytically using Hybrid Optimization of Multiple Energy Resources (HOMER) fig 3 is shown in table 3-4. The simulation was conducted based on 25 years period data. The total battery storage has a nominal capacity of 465kWh with an autonomy of 37.6 hours (which is equal to 37.6 hours of average load). Given that the specific solar irradiation of Umudike as 4.71kWh/m²/day and the average daily energy demand of Mechanical Engineering Department is 180,000 Watts-Hour. The results obtained from various simulations performed by HOMER is summarized in fig.4. HOMER tends to minimize cost, the optimal result (the result with the least cost) is placed at the top, while other results are

kept below it, the optimal result is also known as the winner and it is kept above. The total energy produced by the system 108,239, with the COE of $0.829.
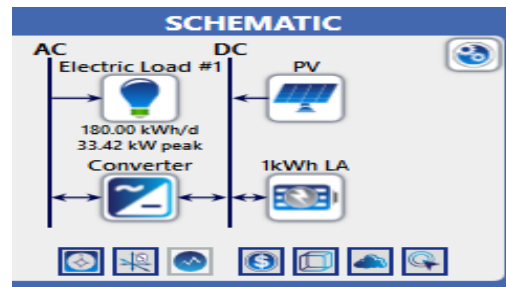

Fig. 3. Schematic diagram of PV standalone system in HOMER interface

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Table 3: Inverter data

PV array	Quantity
Lifetime	10 years
Cost of investment	$300/kW
Cost of O&M	$0/yr
Cost of replacement	$300/kW
Input efficiency	95%

Table 4: Battery data

PV array	Quantity
Lifetime	10 years
Cost of investment	$300/kW
Cost of O&M	$10/yr
Cost of replacement	$300/kW

From the categorized result of fig. 4, it can be deduced that to meet the 180,000Wh/d (180kWh/d) electricity need of Mechanical engineering department of MOUAU, a PV System of 78.2kW power output is required with an initial capital cost of $330,211, total net present cost (NPC) of $442,683 and a minimum cost of energy (COE) of $0.829. The system also has an annual operating cost of $13,355. The energy yield of the PV system is shown in Fig 5.

The system has its total annual electricity production as 108,239kWh/yr, total annual consumption of electricity as 63,442kWh/yr and an excess electricity of 44,797kWh/yr. The system is totally renewable, as it has renewable fraction of 100%. Umudike is rich with abundant sun light which is first free in nature, abundant in supply and it can be easily harness to generate electricity for use in mechanical engineering department of Michael Okpara University of Agriculture, Umudike. Table 5 contains the summary of the electric load of the system. The system uses alternating current (A.C) loads, for this simulation, the load of the system was set at A.C. load.
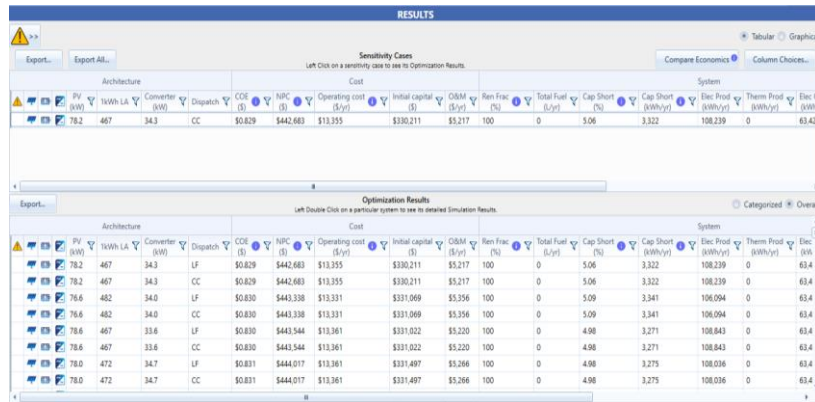
Fig. 4. Optimal simulation result with HOMER

Table 5 Electricity data

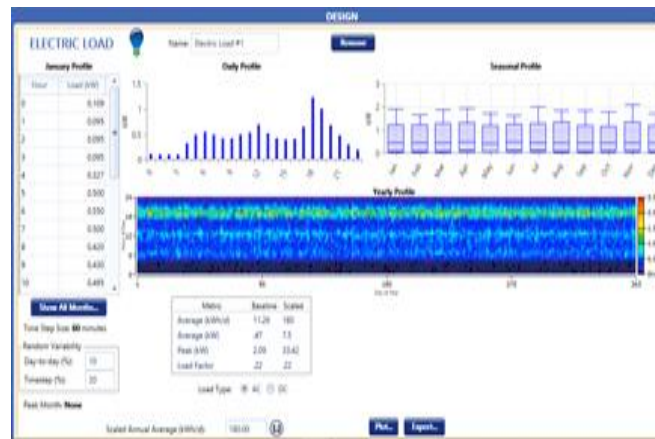| Matric	Baseline	Scaled
Average (kWh/d)	11.26	180
Average (kW)	0.47	7.5
Peak(kW)	2.9	33.42
Load factor	22	22

Fig. 5. Monthly electricity production with the PV system.

Fig. 5 contains the daily load profile of the system showing the time of the day and the power produced at that given time. It also has the seasonal load profile of the system fig. 5 also shows the relationship of average energy generated data to all the months of the year. It can be seen that November has the highest average annual maximum solar energy, average daily maximum solar energy, average energy, daily average minimum and annual minimum. While June has the lowest average annual maximum solar energy, average daily maximum solar energy, average energy, daily average minimum energy and annual minimum. The fig. 6 shows the scaled data for the average daily profile of electrical energy produced. It shows the hour by hour solar energy generation, for the 24 hours of each day and all the months of the year. Fig. 7 is a data map (D Map) it shows one year of time series data. With the time of day on one axis and day of the year on the other, each time step of the year is represented by a rectangle which is colored according to the data value for that hour. The D Map format often allows you to see daily and seasonal patterns easily than you could with a simple time series plot. The D Map in fig. 7 shows solar radiation over a year. Fig. 7 illustrates the interactions of the renewable energy. It shows the time of the day that the PV System generates electricity for use. It also indicates the relationships between 24 hours of the day and the 365 days of the year as regards the output renewable energy generation.
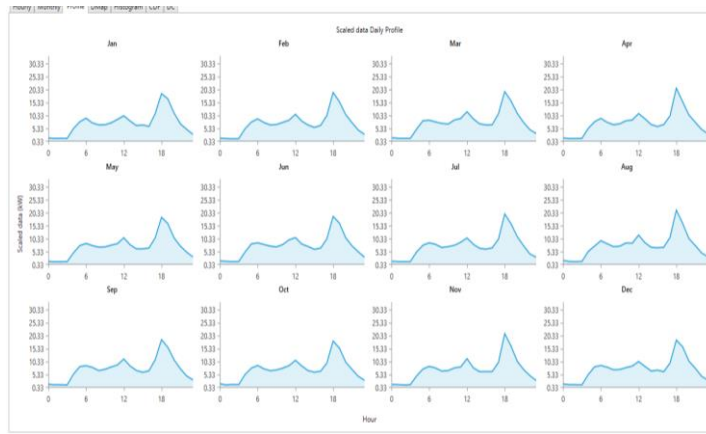
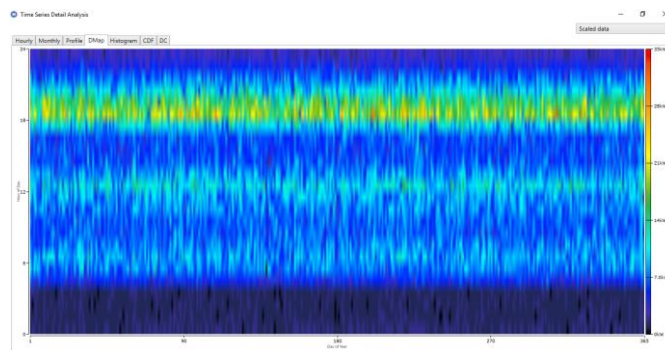**Fig. 6.** Average hourly energy generation of all the months of the year.

Fig. 7. Hourly energy generation of energy of MOUAU
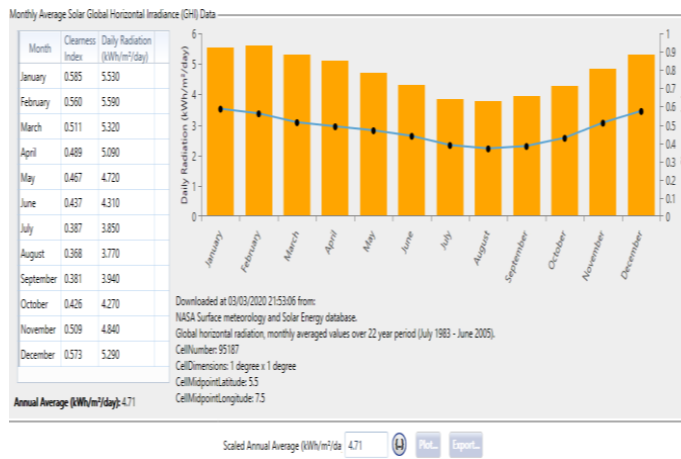

Fig. 8. Average monthly solar global horizontal irradiance of MOUAU.

Fig. 8 shows some of the data that were used by HOMER software to perform the simulation taking note of the specified location so as to generate an accurate result. It can also be seen that the months of January, February, November and December has a very high annual electricity generation, which indicates that those months has minimal rainfall, while the months of July and August has less energy generation at such more rainfall is experience in the months of July and August. From the fig. 8 shows that annual average daily solar radiation of Michael Okpara University of Agriculture, Umudike as 4.71kWh/m^2/day. It also comprises of the cell dimension of 1 degree by 1 degree. Cell midpoint latitude of 5.5 and Cell midpoint longitude of 7.5. Fig. 8 also contain the cleanness index of all the months of the year. The PV stand-alone system is environmentally friendly as no emission is released to the atmosphere. The system is noiseless and causes no environmental pollution.

Conclusion: From the computational result obtained, it shows clearly that the PV System can generate sufficient and dependable energy for Umudike. Since Umudike is enriched with a high level of solar radiation, a considerable fraction of its energy requirements may be tapped from solar energy. The use of PV standalone system as an alternative source of energy to generator as it reduces combustion of fossil fuels and the consequent carbon dioxide CO_2 emission which is the principal cause of the greenhouse-effect and global warming. From the obtained computational result of Photovoltaic System using HOMER software it shows that all through the year the PV system produces power and hence it is good for continuous power generation throughout the year. This indicates that the PV Stand-alone System is worthwhile for Umudike electrification, as it generates sufficient energy and is also environmentally friendly because of the reduction in emission of greenhouse gases and other pollutants which is associated with diesel generator.

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