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Optimization of Solar Panel Tilt and Azimuth Angle for Maximum Solar Irradiation and Minimum Loss for Rural Electrification

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Abstract:** The earth receives solar power at a rate of 120 petawatts, meaning that the energy obtained from the sun in a single day could satisfy the world's energy needs for almost twenty years. Africa is often considered and referred as the "Sun continent" or the continent where the Sun's influence is the greatest, yet over 600 million people in sub-Saharan Africa live without electricity. This inexhaustible, untapped, abundant, and environmentally friendly solar energy potential encouraged solar power generation technologies to flourish faster than any other renewable energy technology most especially in Africa. The amount of electricity generated by a fixed-tilt solar PV system depends on the orientation of the PV panel (tilt and azimuth angle) relative to the sun. The panel of a solar PV system collect solar radiation more efficiently when the sun's rays are perpendicular to the panel: when the sun hits it directly at a 90^o degree angle; but the sun is a moving target. Not only does it move across the sky throughout the day, but it is higher in the sky in the dry season (winter) from October to March and lower in the sky in the wet season (summer) from April to September. Since the climate is usually characterized into two seasons, the system optimization presented in this paper was carried out based on: yearly irradiation yield (fixed tilted plane) to guarantee optimum solar irradiation throughout the year, with 0.0% loss with respect to optimum. The system eliminates the challenges associated with changing the solar panel orientation every season, or using the expensive and inefficient sun tracker in tracking sun energy; while guaranteeing higher energy production, better system performance, lower system losses, and low operational cost. The system optimization was carried out with the "PVsyst simulation software" made for PV system designers and researchers to predict the performance of different solar system configurations, evaluate the results, and identify the best approach for maximum energy production. This paper investigated the optimal tilt and azimuth angle for solar panel orientation techniques for a typical rural community in Nigeria (Ndikelionwu) to advance rural electrification. After series of simulation and optimization processes; the best yearly irradiation yield was recorded when the solar panel is at 40^o tilt and 0^o Azimuth angle; with 0.0% loss with respect to optimum.

Keywords:** Optimization, PVsyst, Solar Irradiation, Tilt and Azimuth Angle, Global on Collector Plane, Fixed Tilted Plane, Rural Electrification, Solar Panel Orientation And Yearly Irradiation Yield.

I. INTRODUCTION

The depletion of conventional energy resources, the increasing evidence of global warming and the rapid growth of the world's population have led to a noticeable increase in focus on the implementation of renewable energy technologies during the last decade [1]. Among all renewable energy resources, solar energy is by far the most abundant source of energy [2]. According to the World Sunshine Map, Africa receives many more hours of bright sunshine during the course of the year than any other continent of the world [3]. Despite the large solar potential in Nigeria, penetration of solar power in Nigeria's energy sector is still very low. Considering the situational background of the research area, this paper attempts to build a tangible solution to; low energy production, poor system performance, high system losses, and high operational cost associated with solar energy systems as a result of wrong orientation or installation of solar panel (tilt and azimuth angle). The work sought to advance rural electrification by optimizing and simulating an off-grid (standalone) solar energy system to serve rural dwellers with limited access to electricity, or those not reached by National grid, or for areas too sparsely populated to build a local mini-grid. In this paper, optimization of solar panel orientation is done for Ndikelionwu, a typical rural community in Nigeria; to find out the best orientation or installation angle for solar panel in a fixed tilted plane for maximum global on collector plane, and minimum possible loss with respect to optimum.
The optimization process involves varying the tilt angle of the solar panel from 10^0 to 60^0 at 0^0 azimuth angle for maximum yearly irradiation yield. The optimization technique presented in this paper eliminates the use of the expensive and inefficient sun tracker; while guaranteeing higher energy production, better system performance, lower system losses, and low operational cost.

The system optimization and simulation processes were carried out using the “PVsyst simulation software”. Pvsyst is a powerful and versatile PV software designed to be used by engineers and researchers for the study, sizing, optimization, simulation, configuration, energy prediction, and data analysis of complete PV system (whether off-Grid or grid connected).

II. OPTIMIZATION TECHNIQUES

A. System Optimization

Optimization is the process of making a design or system more effective or functional [4]. The investigation of the influencing operational parameters as well as optimization of the solar energy system is the key factors to enhance the power conversion efficiency. Optimization of solar energy system is the process of adjusting some specified set of parameters to make the best or most effective use of the system without violating some constraints. The parameter presented in this paper is the panel orientation (tilt and azimuth angle). The most common goals are minimizing cost and maximizing throughput and/or efficiency. This is one of the major quantitative tools in solar energy system. When optimizing a process such as off-grid solar energy system, the goal is to maximize one or more of the process specifications, while keeping all others within their constraints. This can be done by using a process mining tool, discovering the critical activities and bottlenecks, and acting only on them.

The orientation of the solar panel (Tilt and Azimuth angle) is one of the best ways to guarantee that the solar panel operates at their optimum, which forms the background of this paper. The main objective of the optimization technique presented in this paper is to maximize the solar irradiation incident on the PV array by optimizing the tilt and azimuth angle of the collecting surface for highest yearly irradiation yield, with minimum loss with respect to optimum.

B. Fixed-tilted system (yearly irradiation yield)

The type of PV system presented in this paper is the “fixed-tilted system” that will guarantee yearly irradiation yield. The fixed-tilted system is used to determine the best orientation of the solar panel throughout the year; instead of varying the tilt and azimuth angle of the solar panel every season (wet/dry season), or using the expensive and inefficient sun tracker in tracking sun energy for best system performance. The amount of electricity generated by a fixed-tilted solar PV system depends on the orientation of the PV panel relative to the sun. The panel of a solar PV system collect solar radiation more efficiently when the sun's rays are perpendicular to the panel. In recent years, solar power plants have increasingly been installed with tracking systems instead of fixed-tilted systems. Tracking systems either rotate on a single axis (typically east to west) or on a dual axis, but this method of tracking the sun energy for best system performance is expensive and inefficient. It is all about the direction the solar panel is facing, often called the Azimuth angle; and the tilt angle, which is the installation angle of the solar panel. Figure 1 shows the tilt angle and the Azimuth angle for solar panel orientation.

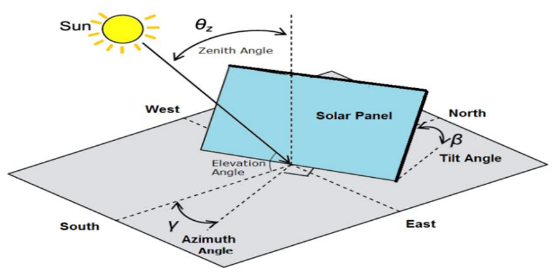

Fig. 1: Tilt and Azimuth Angle [5]

Fixed-tilted PV systems use two separate angles that determine their orientation relative to the sun: the azimuth angle and the tilt angle. Both angles have great impact in the system optimization. The minimum angle of tilt should be 15 degrees and maximum 62 degrees.

1) *The azimuth:* The azimuth angle specifies the compass direction that a tilted panel is facing: north, south, east, or west. Most panels in the Northern hemisphere are south-facing. The Azimuth angle can also be seen as the angle of the sun’s rays measured in the horizontal plane from due south (true south) for the northern hemisphere or due north for the southern hemisphere.
2) *The tilt:* The tilt angle is the angle from the horizontal ground. A tilt of zero degrees means that the panel is lying flat on the ground, while a tilt of 90 degrees means that the panel is perpendicular to the ground, like on the side of a building. The tilt angle can also be defined as the angle the panel makes with respect to the horizontal ground. The best tilt angle for every location is the tilt which maximizes the total annual irradiation.

C. Mathematical Model for the Optimization of an off- Grid solar energy system

Assuming initial constant values to be G_{SC}, φ, ρ_g, and H. N is set to one, meaning the first day of the year after the surface is tilted from 0 to 90 degrees for given day and obtain the optimum tilt angle at maximum irradiance. Next, n is increased by one and continue to find the optimum tilt angle at given day and is continued till the value of 365 (complete year). The need for this optimization is to find the best orientation or installation angle for the solar panel: tilt and azimuth angle, for best solar irradiation and minimum loss with respect to optimum.

Tilt angle is varying from 0 to 90 degrees with one degree step size for accurate results. For finding irradiances, one will have to calculate the values of δ, ω_s, and ω_{ss}, then Ho, K_T, H_d, H_b, R_d, R_b, and H_T .

Where:

H_T: Total solar radiations received on tilted surface.
H_b: Solar beam radiations on horizontal surface.
R_b: Tilt coefficient to calculate direct solar direct radiations.
H_d: Solar diffused radiations on horizontal surface.
R_d: Tilt coefficient to calculate solar diffused radiations.
H: Global solar radiations on horizontal surface.
ρ_g: Ground reflectivity coefficient.
β: Tilt angle of surface.
ω_{ss}: Sunrise hour angle on tilted surface.
ω_s: Sunset hour angle on horizontal surface.
Ø: Latitude of the place.
δ: Declination angle of the earth.
n: Counted number of days.
K_T: Clearness index.
***H_o*:** Monthly average daily extraterrestrial radiation.

According to [6][7][8]; the equation used to calculate the total solar radiation on the tilted surface is given as:

$$H_T = H_b * R_b + H_d * R_d + H * P_g * \left(\frac{1-\cos\beta}{2}\right) \quad \ldots\ldots (2.1)$$

From equation 2.1 above, the R_b *and* R_d are the tilt coefficients to calculate the beam solar radiation and the diffused solar radiation on the tilted surface, respectively. According to [6][7][8][9]; the coefficient can be determined by equations (2.1) and (2.6).

$$\frac{(\cos(\text{Ø}-\beta) * \cos(\delta) * \sin(w_{ss})) + \left(w_{ss}\left(\frac{\pi}{180}\right)\sin(\text{Ø}-\beta)\sin(\delta)\right)}{(\cos(\text{Ø}) * \cos(\delta) * \sin(w_s)) + \left(w_s\left(\frac{\pi}{180}\right)\sin(\text{Ø})\sin(\delta)\right)} \quad \ldots\ldots (2.2)$$

Where P_d is the ground reflectance (reflectance of ground = 0.2), β is the optimum tilt angle and it is the angle on which PV panel received maximum amount of solar radiations, Ø is the latitude. Ndikelionwu is located at: latitudes: 6, 0833 (64'59.988"N) and longitude: 7, 1333 (77'59.988"E) and δ is the declination angle of the earth and can be calculated by:

$$\delta = 23.45 \sin\frac{360\,(n + 284)}{365} \quad \ldots\ldots (2.3)$$

Where ω_s is the sunset hour angle on horizontal surface, which is equal to:

$$\omega_s = \cos^{-1}[-\tan\delta\tan\varphi] \quad \ldots\ldots (2.4)$$

Where ω_{ss} is the sunrise hour angle of inclined plane (tilted surface) and can be calculated as:

$$\omega_{ss} = \min[\cos^{-1}[-\tan\delta\tan\varphi), \cos^{-1}(-\tan(\text{Ø}-\beta)\tan\text{Ø})] \ldots\ldots (2.5)$$

The R_d, which is the coefficient diffuse solar radiation on the tilted surface, can be calculated as:

$$R_d = \frac{H_b}{H_n} * R_b + \left(1 - \frac{H_b}{H_n}\right) * \left(1 + \frac{\cos\beta}{2}\right) * [1 + \sqrt{\frac{H_b}{H}} * \sin(\beta/2)^3] \ldots\ldots (2.6)$$

Where H_b is the beam direct radiation incident angle, calculated by the equation:

$$H_b = H - H_d \quad \ldots\ldots (2.7)$$

Here, H is the global solar radiations at horizontal surface. The data related to global solar radiations on horizontal surface is taken from NASA database.

H_d is the solar diffused radiations at horizontal surface calculated by [6][10][11].

$$H_d = 1.00 - 1.13KT \quad \ldots\ldots (2.8)$$

K_T is the clearness index.

The clearness index is a measure of the clearness of the atmosphere. It is the fraction of the solar radiation that is transmitted through the atmosphere to strike the surface of the earth. And it can be calculated from the equation below:

$$K_T = \frac{H}{Ho} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (2.9)$$

H and Ho in equation 2.9 above are global solar radiations on horizontal surface and monthly average daily extraterrestrial radiation (kwh/m^2/day) and can be calculated by:

$$Ho = \frac{24}{\pi} G_{sc}\left(1 + 0.33\cos\frac{360n}{365}\right) * (\cos\emptyset \cos\delta \sin\omega_s + \pi\, \omega_{s/180} \sin\varphi \sin\delta) \ldots\ldots\ldots (2.10)$$

In equation 2.10 above, the G_{sc} is the solar constant referred as 1353 W/m^2 in [10]. Other parameters are taken as constant values. Using equations 2.1 to 2.10, one can calculate the irradiance at different supposed tilted angle. The procedure for finding the optimum tilt angle of the off-Grid solar energy solution is shown in figure 2 below.

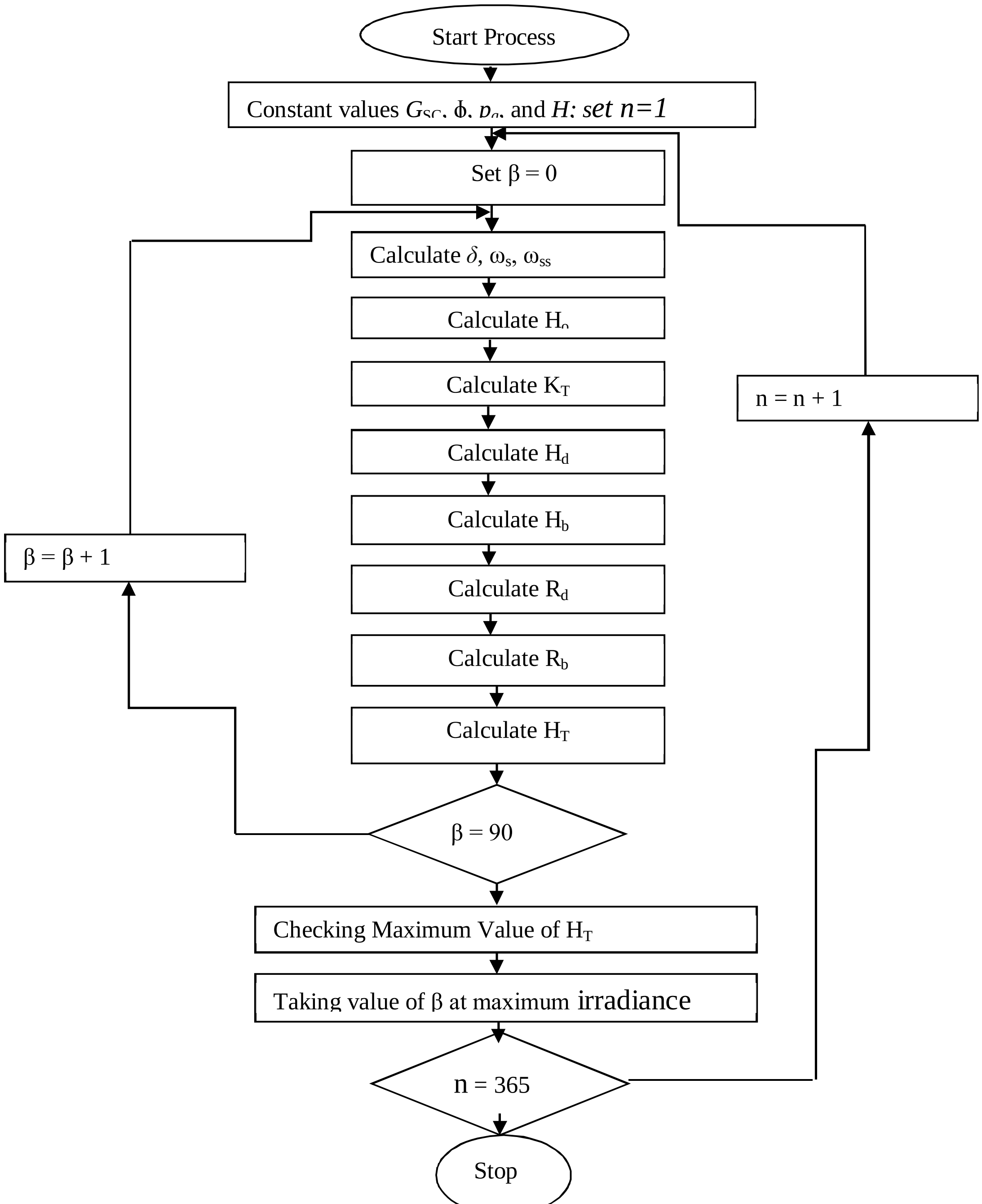

Fig. 2 Flowchart for the optimization of tilt angle

D. Off-grid (standalone) PV systems

A simple standalone PV system is an automatic solar system that produces electrical power to charge banks of batteries during the day for use at night when the suns energy is unavailable. A standalone small scale PV system employs rechargeable batteries to store the electrical energy supplied by a PV panels or array. Standalone PV systems are ideal for remote rural areas and applications where other power sources are either impractical or are unavailable to provide power for lighting, appliances and other uses. In these cases, it is more cost effective to install a single standalone PV system than pay the costs of having the local electricity company extend their power lines and cables directly to the home. A standalone photovoltaic (PV) system is an electrical system consisting of an array of one or more PV modules and batteries, inverter, charge controller, and one or more loads. The simplified off-Grid (standalone) PV system is shown in figure 3.

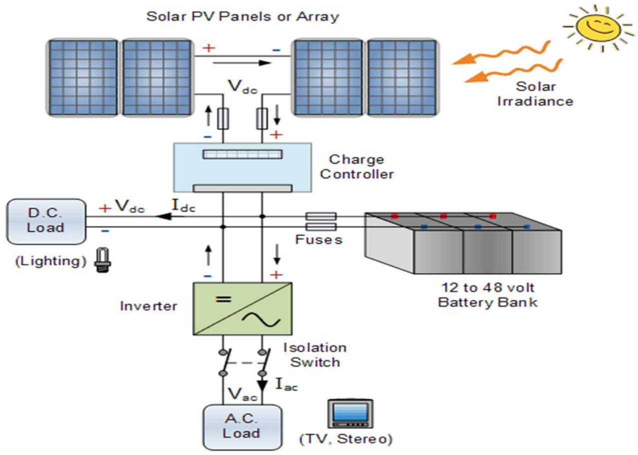

Fig. 3 off - Grid Standalone PV System [12]

E. PVsyst Simulation Software

PVsyst is one of the oldest photovoltaic software, developed by University of Geneva. PVsyst is designed to be used by architects, engineer and researchers and it is also a very useful pedagogical tool. PVsyst is simulating software used for the study, sizing and data analysis of complete PV systems. It includes extensive meteorological and PV systems components databases, as well as various solar energy tools: meteorological graphs, solar geometry parameters, irradiation models, PV-array behaviour under partial shadings, optimizing tools for orientation, etc. The PVsyst software is geared to the needs of solar energy installers, engineers, and researchers. It is also very helpful for educational training. The version used in the optimization and simulation of the system presented in this paper is the “PVsyst 7.1 version”. Figure 4 shows the PVsyst 7.1 simulation environment and the three main areas where the software can be used: Grid-connected solar energy system, off-Grid solar energy system, and water pumping system; while figure 5 shows the project execution environment of the PVsyst simulation software.

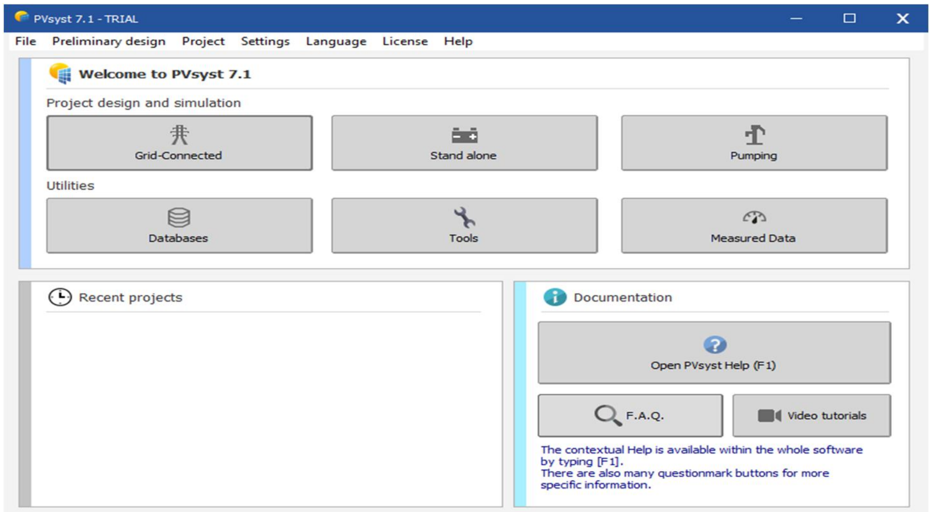

Fig. 4 The PVsyst 7.1 simulation software environment

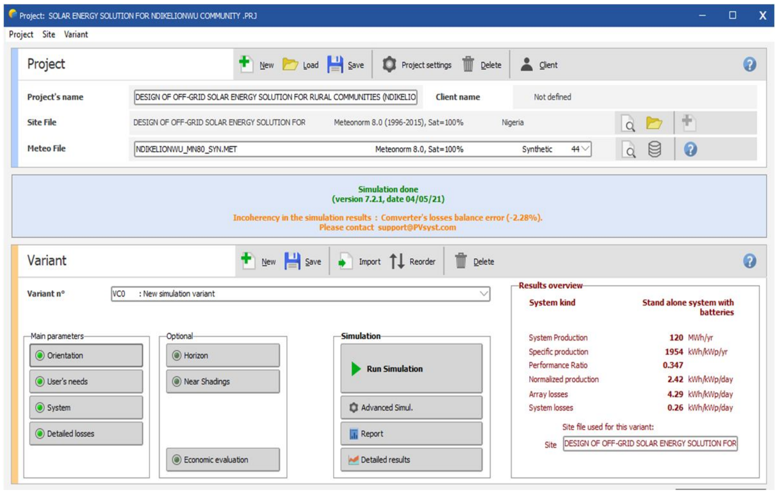

Fig. 5 Project execution environment of the PVsyst simulation software

F. Data Acquisition Plan

The data acquisition plan relates to the collection of primary data pertinent to optimize and conduct the technical analysis of the off-Grid solar energy system under consideration. The following steps were taken to acquire the necessary data and information needed to effectively carry out the system optimization.

G. Optimization parameters

The optimization parameters relate to information needed to successfully optimize and determine the best tilt and azimuth angle for the installation of the solar panel: for highest global on collector plane (solar irradiation) and minimum loss. These optimization parameters are:

- Project Location.
- Sun-path of the project location
- The meteorological data available for the project location, and
- The solar panel orientation (installation angles: tilt and azimuth angle). These are briefly discussed below.

1) *Project Location:* Information about the geographical location of the project site is the most important parameter needed to successfully carry out the system optimization. This information is basically the "latitude and longitude" of the project site. Once the location (project site) is selected, the PVsyst software automatically loads the basic information related to the project site to the simulation window. The project location (Ndikelionwu) is located at: latitudes: 6, 0833 (64'59.988"N) and longitude: 7, 1333 (77'59.988"E).
2) *Sun path of the project location:* This shows the path of the Sun across the sky from wet season (summer) to dry season (winter) for the particular project location (Ndikelionwu). The sun path of the project site is shown in figure 6.

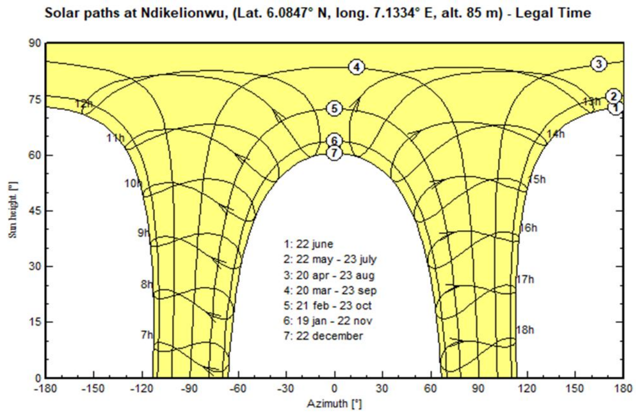

Fig. 6 The sun path diagram of the project site

One of the first requirements in solar system design is to understand sun path diagram of a given location which shows the path of the sun across the sky from wet season (summer) to dry season (winter). Sun path, sometimes also called day arc, refers to the daily and seasonal arc-like path that the Sun appears to follow across the sky as the earth rotates and orbits the Sun. The Sun's path affects the length of daytime experienced and amount of daylight received along a certain latitude during a given season. The relative position of the Sun is one of the major factors in the heat gain of buildings and in the performance of solar energy systems. Accurate location-specific knowledge of sun path and climatic conditions is essential for economic decisions about solar collector area.

3) *Meteorological Data:* With regards to the environmental analysis, secondary data available from the PVsyst software (Meteo data) was used.

a) *Meteonorm:* Meteonorm is a powerful software tool of the "PVsyst simulation software" that allows the system designer to access data about solar radiation and other weather parameters around the world. Although the program has a straightforward interface, the correct interpretation of the data provided depends on knowledge well beyond being able to use the software. Meteonorm generates accurate and representative typical years for any place in the earth, including Ndikelionwu: the case study presented in this paper. The database of Meteonorm consists of more than 8 000 weather stations, five geostationary satellites and globally calibrated aerosol climatology. It is a unique combination of reliable data sources and sophisticated calculation tools. It provides access to typical years and historical time series. The Meteonorm available of the PVsyst simulation software is shown in figure 7. The Meteo database contains valuable information (data) about the geographical site of almost any project location in the world, Synthetic data, Meteo tables/graphs, among other important information (data) needed to design, optimize, and simulate any Grid connected or off-Grid solar energy system.

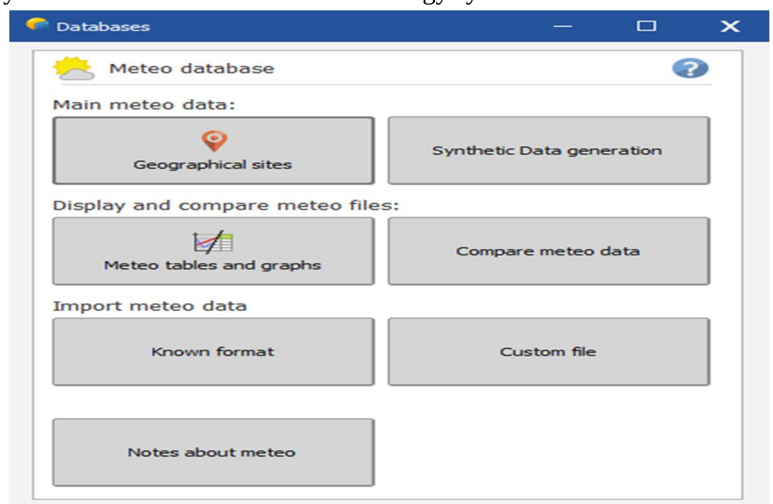

Fig. 7 The Meteonorm (Meteo database) of the PVsyst simulation software

PVsyst distinguishes two kinds of Meteorological data:

b) *Monthly Meteo Data (*.SIT files)*

Which are associated with every geographic site. Monthly data are used to build the hourly data. Monthly meteo files contain:

- The site name, the country, the world region.
- The geographical coordinates: latitude, longitude, altitude and Time zone.
- The monthly Global Horizontal Irradiation (GHI or GlobHor).
- The monthly averages of the ambient temperature.

The files may also include optional data:

- The monthly Diffuse Horizontal Irradiation.
- The monthly average of Wind Velocity.

c) Hourly meteo data (.MET files)*

Hourly meteo data contains the hourly values of:

- Global Horizontal Irradiation (GlobHor or GHI).
- Diffuse Horizontal Irradiation (DiffHor).
- Ambient temperatures.
- Wind Velocity (if available).

The data are recorded for whole days (0H - 23H). Step labels are referred to the beginning of the interval (i.e. the 12 hour label corresponds to the 12-13 hour interval). The monthly/yearly values of the Global Horizontal Irradiation (GlobHor or GHI) and Diffuse Horizontal Irradiation (DiffHor) and the corresponding temperature is shown in figure 8, while the Meteo data for the project site: synthetically generated data from monthly values is shown in figure 9.

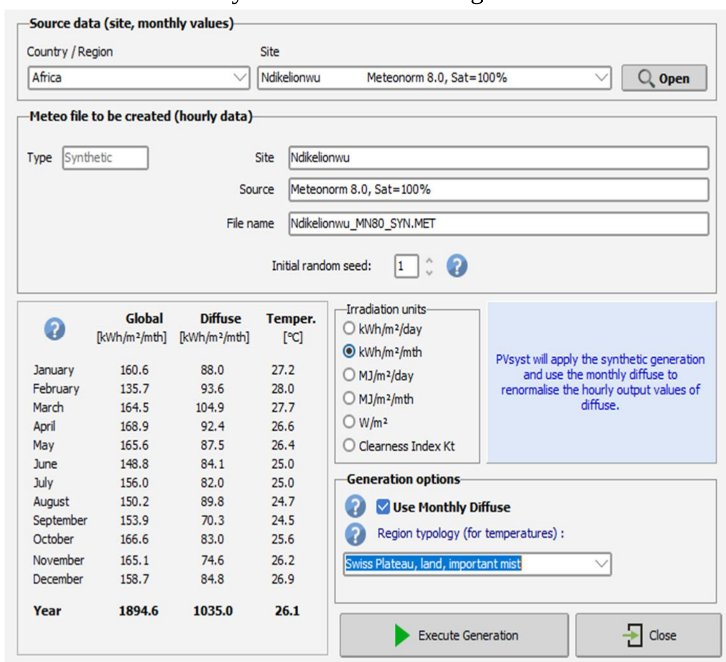

Fig. 8 Monthly/yearly values of the GHI and the DHI and the corresponding temperature

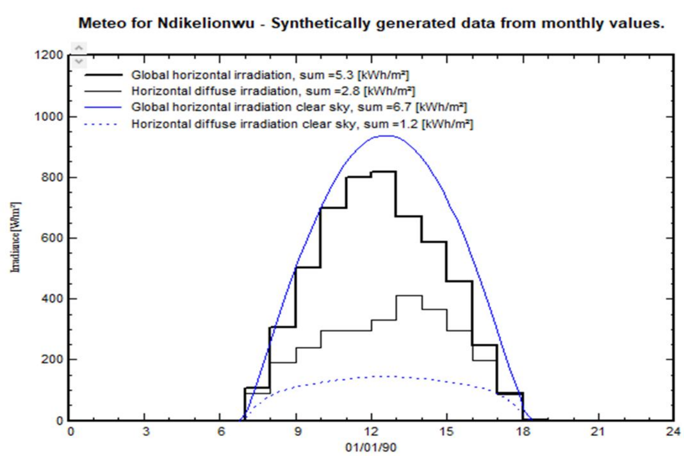

Fig. 9 Meteo for the project site as generated by the PVsyst simulation software

4) *System optimization based on fixed tilted plane (yearly irradiation yield):* The sun is higher in the sky in the dry season (winter) and lower in the sky in the wet season (summer). With fixed tilted plane, the idea is to install the solar panel to perform optimally throughout the year (yearly irradiation yield), instead of changing the solar panel orientation or installation angle every season, or using expensive and inefficient sun tracker in tracking sun energy for best system performance.

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In PVsyst simulation software, optimization is with respect to:

a) *Dry Season (winter: October – March):* During the system optimization, peak/best possible value was obtained during the dry season (winter) as can be seen in the "plane tilt" and "plane orientation" graph in figure 10. With tilt angle of 60^o and Azimuth of 0^o the system gave 0.0% loss with respect to optimum, with Global on collector plane of 1541kWh/m^2 (solar irradiation).

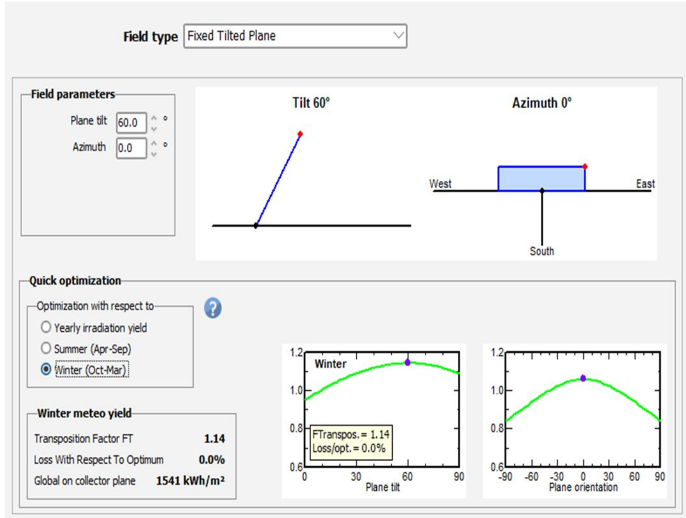

Fig. 10 Dry Season (winter) optimization at tilt angle of 60^o and Azimuth of 0^o

b) *Wet Season (summer: April – September):* During the system optimization, a poor value was generated during the wet season (summer) as can be seen in the "plane tilt" and "plane orientation" graph in figure 11. So with the same tilt angle of 60^o and Azimuth of 0^o (as for dry season above), the system gave -8.6% loss with respect to optimum, with Global on collector plane of 1541 kWh/ m^2.

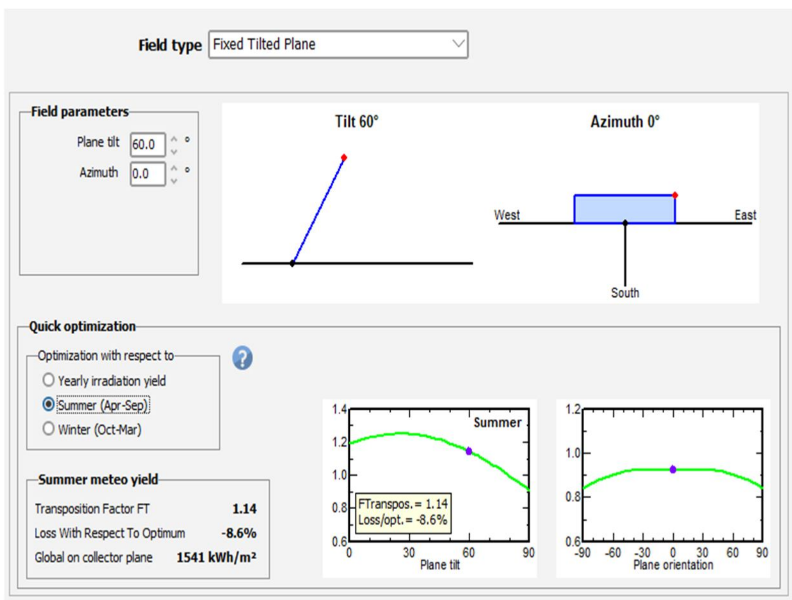

Fig. 11 Wet Season (summer) optimization at tilt angle of 60^o and Azimuth of 0^o

By adjusting the dry season/winter result to the best value (varying the tilt and azimuth angle), it affects the summer result; and by adjusting the wet season/summer result to best value, it affects the winter result.

So if one is working in a project that will be constructed or effective in the summer months only, one can make the angle to the best value at the wet season (summer). Also, if one is working in a project that will be constructed or effective in the dry season (winter) only, one can make the tilt and azimuth angle to the best value at the dry season.

c) *Yearly Irradiation Yield (Non Seasonal: January - December):* This paper presented a global design that works throughout the year (January – December). So the system was optimized based on "yearly irradiation yield", not seasonal. Considering the above scenarios: wet and dry season with tilt angle of 60^o and Azimuth of 0^o; the result generated for yearly irradiation is shown in figure 12. It shows a system with - 5.4% loss with respect to optimum, with Global on collector plane of 1541 kWh/ m^2.

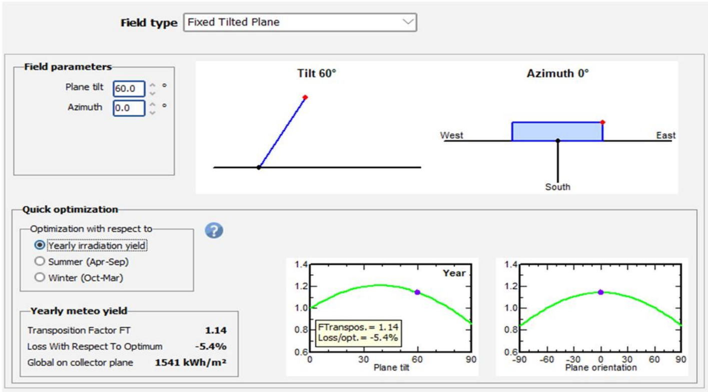

Fig. 12 Yearly Irradiation optimization at tilt angle of 60^o and Azimuth of 0^o

The best orientation (system optimization) presented in this paper is shown in figure 13. The best yearly irradiation yield occurred when the solar panel was installed at 40^o tilt and 0^o Azimuth angle. At this point, 0.0% loss was recorded with respect to optimum and Global on collector plane: solar irradiation received by the solar panel was 1629 kWh/m^2, against the 1541 kWh/ m^2 obtained when the solar panel was installed at 60^o tilt and 0^o azimuth (for both wet and dry season).

For all the optimization for different tilt angle between 10^0 and 60^0 at 0^0 azimuth angle: the highest solar irradiation occurred at 40^o tilt angle and 0^o Azimuth angle as clearly shown in table 1: the optimization table for different tilt and azimuth angle. The table shows tilt angle and azimuth angle for: yearly irradiation yield, wet season (summer), dry season (winter); as well as the global on collector plane (solar irradiation), and the associated loss with respect to optimum.

The system performs optimally: at its best with 0.0% loss, when the solar panel was installed at 40^o tilt and 0^o Azimuth angle. So at Ndikelionwu, a typical rural community in Nigeria (used as case study); solar panel must be installed at 40^o tilt and 0^o azimuth angle for optimum system performance: High energy productions, better system performance, and lower system losses. The final orientation (system optimization) graph and values is shown in figure 14.

The "Transposition Factor (FT)" is the ratio of the incident irradiation on the plane, to the horizontal irradiation; i.e. what one gain (or loose) when tilting the collector plane.

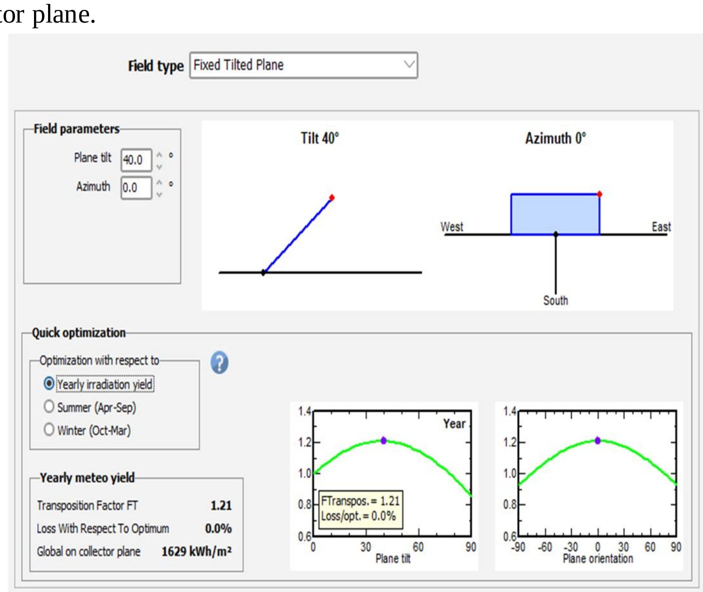

Fig. 13 Yearly Irradiation optimization at tilt angle of 40^o and Azimuth of 0^o

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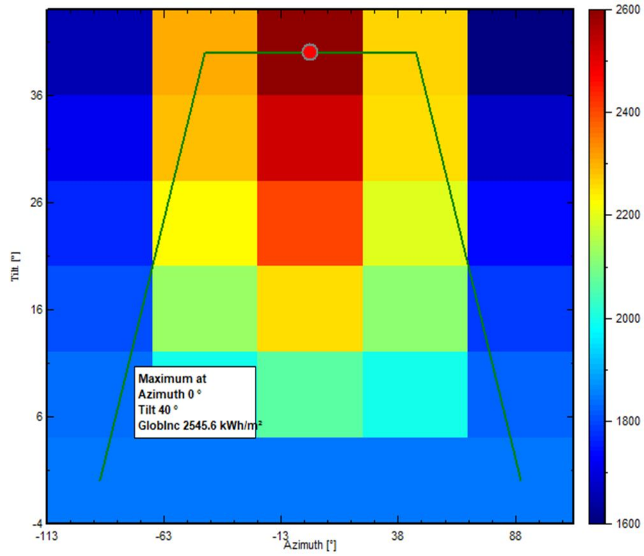

Fig. 14 The final system optimization graph and values as generated by the PVsyst simulation software

TABLE 1
Optimization table for different tilt/azimuth angle and their corresponding values

S/N	Tilt angle	Azimuth Angle	Global on Collector Plane (Yearly Meteo Yield) and the associated Loss due to Optimum	Wet Season (Summer: April – Sept.)	Dry Season (Winter: October – March
1	10^0	0^0	1474Kwh/m^2 (Loss: -9.5%)	1474Kwh/m^2 (Loss: -1.9%)	1474Kwh/m^2 (Loss: -11.1%)
2	15^0	0^0	1523Kwh/m^2 (Loss: -6.5%)	1523Kwh/m^2 (Loss: -0.9%)	1523Kwh/m^2 (Loss: -9.0%)
3	20^0	0^0	1562Kwh/m^2 (Loss: -4.1%)	1562Kwh/m^2 (Loss: -0.3%)	1562Kwh/m^2 (Loss: -7.1%)
4	25^0	0^0	1593Kwh/m^2 (Loss: -2.2%)	1593Kwh/m^2 (Loss: -0.1%)	1593Kwh/m^2 (Loss: -5.5%)
5	30^0	0^0	1615Kwh/m^2 (Loss: -0.9%)	1614Kwh/m^2 (Loss: -0.3%)	1614Kwh/m^2 (Loss: -4.1%)
6	35^0	0^0	1627Kwh/m^2 (Loss: -0.1%)	1626Kwh/m^2 (Loss: -0.8%)	1626Kwh/m^2 (Loss: -.2.9%)
7	40^0	0^0	1629Kwh/m^2 (Loss: 0.0%)	1629Kwh/m^2 (Loss: -1.6%)	1629Kwh/m^2 (Loss: -1.8%)
8	45^0	0^0	1622Kwh/m^2 (Loss: -0.5%)	1621Kwh/m^2 (Loss: -2.9%)	1621Kwh/m^2 (Loss: -1.0%)
9	50^0	0^0	1604Kwh/m^2 (Loss: -1.5%)	1604Kwh/m^2 (Loss: -4.5%)	1604Kwh/m^2 (Loss: -0.5%)
10	55^0	0^0	1577Kwh/m^2 (Loss: -3.2%)	1577Kwh/m^2 (Loss: -6.4%)	1577Kwh/m^2 (Loss: -0.1%)
11	60^0	0^0	1541Kwh/m^2 (Loss: -5.4%)	1541Kwh/m^2 (Loss: -8.6%)	1541Kwh/m^2 (Loss: -0.8%)

III. RESULTS

Optimization of solar panel tilt and azimuth angle for an off-grid solar energy system in a typical rural community was performed using "PVsyst simulation software". The software was used to optimize the tilt and azimuth angle of the solar panel to guarantee higher energy production, better system performance, lower system losses, and low operational cost. Some useful results: data, graph, and tables generated by the PVsyst simulation software during system simulation are shown below.

A. Discussion of Some Important Tables as Generated by the Pvsyst Simulation Software

1) *Incident Energy:* Incident energy is a measurement of energy, usually heat, striking a surface. If you were sitting near a campfire, the warmth you would feel would come from the radiant heat of the fire, and it could be measured in terms of incident energy [13]

In most cases, the incident energy depends on three elements:

a) The intensity of the source of energy.
b) The distance between the source and the surface where the energy is measured.
c) The duration of the exposure.

If one of those elements changes; the incident energy will also change. The meteo and incident energy as calculated by the PVsyst simulation software is presented in table 2.

Table 2
The meteo and incident energy of the optimized solar energy system

	GlobHor	DiffHor	T_Amb	WindVel	GlobInc	DifSInc	Alb_Inc	DifS_GI
	kWh/m²	kWh/m²	°C	m/s	kWh/m²	kWh/m²	kWh/m²	ratio
January	160.6	88.0	27.18	1.6	285.9	53.40	3.609	0.000
February	135.7	93.6	27.98	1.8	208.0	48.88	3.173	0.000
March	164.5	104.9	27.70	2.0	208.6	60.08	3.846	0.000
April	168.9	92.4	26.60	1.8	190.3	53.22	3.946	0.000
May	165.6	87.5	26.36	1.5	169.0	49.21	3.871	0.000
June	148.8	84.1	25.02	1.6	145.5	47.60	3.477	0.000
July	156.0	82.0	25.01	1.9	155.6	47.00	3.646	0.000
August	150.2	89.8	24.67	2.0	159.8	53.84	3.511	0.000
September	153.9	70.3	24.50	1.6	191.0	43.51	3.594	0.000
October	166.6	83.0	25.58	1.3	251.1	52.23	3.895	0.000
November	165.1	74.6	26.15	1.3	297.5	50.15	3.817	0.000
December	158.7	84.8	26.89	1.4	283.3	56.36	3.564	0.000
Year	1894.6	1035.0	26.13	1.6	2545.6	615.47	43.951	0.000

Where;

➢ *Meteorological Data*
- *GlobHor:* Horizontal global irradiation: as read on the meteo file of the PVsyst software.
- *DiffHor:* Horizontal diffuse irradiation: read on the meteo file of the PVsyst software.
- *T_Amb:* Ambient temperature: read on meteo file.
- *Windvel:* Wind velocity: read on meteo file.

➢ *Incident Energy*
- *GlobInc:* Incident global irradiation in the collector plane.
- *DiffSInc:* Incident diffuse irradiation (from sky) in the collector plane.
- *AlbInc:* Incident albedo irradiation in the collector plane

➢ *Secondary Indicators*
- *DifS_Gl:* Incident Sky diffuse/Global ratio (DifSInc/GlobInc).

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2) *Effective incident energy (Transpos, IAM, Shadings)*

Effective: irradiation effectively reaching the PV-cell surface. The effective incident energy (Transpos, IAM, Shadings) table as calculated by the PVsyst simulation software is shown in table 3.

TABLE 3
The effective incident energy (Transpos, IAM, Shadings)

	GlobHor kWh/m²	GlobInc kWh/m²	GlobIAM kWh/m²	GlobEff kWh/m²	DiffEff kWh/m²
January	160.6	285.9	281.6	281.6	51.66
February	135.7	208.0	204.5	204.5	47.29
March	164.5	208.6	205.1	205.1	58.12
April	168.9	190.3	187.2	187.2	51.48
May	165.6	169.0	166.0	166.0	47.61
June	148.8	145.5	142.8	142.8	46.05
July	156.0	155.6	152.8	152.8	45.47
August	150.2	159.8	156.9	156.9	52.08
September	153.9	191.0	187.2	187.2	42.10
October	166.6	251.1	245.8	245.8	50.53
November	165.1	297.5	292.4	292.4	48.52
December	158.7	283.3	279.4	279.4	54.52
Year	1894.6	2545.6	2501.5	2501.5	595.42

The table presents the following variables:

- ➢ *Meteorological Data*
- *GlobHor:* Horizontal global irradiation.

- ➢ *Incident Energy in the Collector Plane*
- *GlobInc:* Incident global irradiation.

- ➢ *Incident Energy On Collectors, Corrected For Optical Losses*
- *GlobIAM:* Global on collectors, corrected for horizon, near shadings and IAM.
- *GlobEff:* Effective global, after all optical losses (shadings, IAM, soiling).
- *DiffEff:* Effective diffuse, corrected for all optical losses.

B. *Discussion of some important graphs as generated by the Pvsyst simulation software*

1) *Reference Incident Energy in Collector Plane:* As the name implies, the reference incident energy in collector plane is the energy (solar irradiation) that reaches the solar panel (collector plane) every month. Figure 15 shows the reference incident energy in collector plane of the designed project. Solar irradiation is higher in the dry season/winter (October – March) compared with wet season/summer (April – September); meaning that more energy is generated in the dry season than in the wet season (as expected).

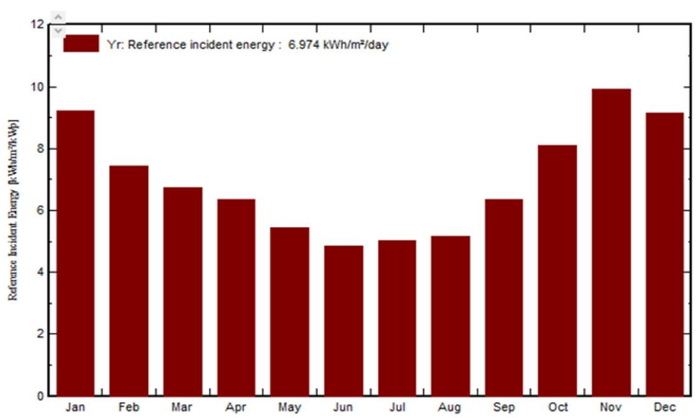

Fig. 15 The reference incident energy in collector plane

2) *Performance Ratio (PR) and Solar Fraction (SF):* Performance Ratio (PR) is the system efficiency during the year and gives information about the impact of overall system losses on the rated output. The losses include PV module, tilt angle, dust, shade, module temperature losses. Results using monocrystalline silicon PV module indicate that during a year, there is fluctuation in the performance of the system [14]. The Performance Ratio (PR) **Yf / Yr**; is the global system efficiency with respect to the nominal installed power and the incident energy.
a) *Yf:* System yield is the system daily useful energy, referred to the nominal power [kWh/KWp/day].
b) *Yr:* Reference system yield is the ideal array yield according to "Pnom" as defined by manufacturer, without any loss. It can be understood as each incident kWh should ideally produce the Array Nominal Power (Pnom) during one hour. Yr is numerically equal to the incident energy in the array plane, expressed in [kWh/m²/day].

It is possible to further improve the performance ratio by using an inverter with higher weighted ratio Maximum Point Power Tracking (MPPT) inverters. The Performance Ratio (PR)/Solar Fraction (SF) graph is shown in Figure 16.

The Solar Fraction (SF): Is the energy demand met from the solar energy. The average solar fraction (SF = Esol/Eload).

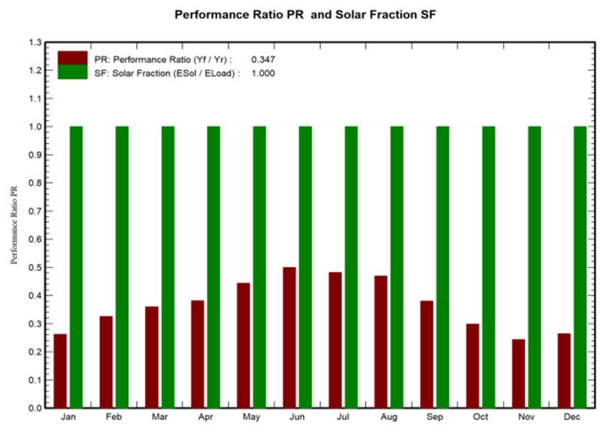

Fig. 16 Performance Ratio (PR) and Solar Fraction (SF)

3) *Incident Irradiation Distribution:* The daily global irradiance distribution over the year is not constant and varies according to local climatic conditions. In Nigeria, the number of hours at high irradiation is generally high. At Ndikelionwu, the diffuse component is high as can been in figure 17: Incident Irradiation Distribution of the project site as generated by the PVsyst simulation software. It shows the graphical representation of global irradiation distribution which ranges from 2 kWh/m^2 to 56 kWh/m^2 against the global incidence in collector plane between 0 to 1200W/m^2.

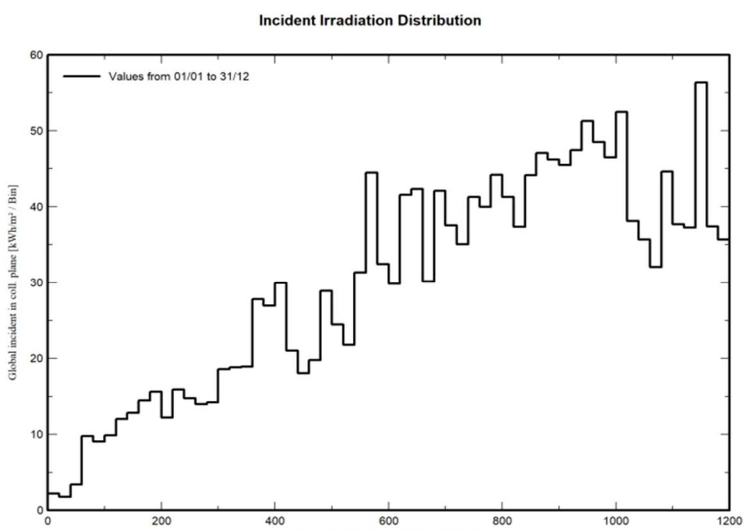

Fig. 17 Incident Irradiation Distribution of the project site

4) *Incident Irradiation tail Distribution:* Figure 18 shows that the cumulated global incident irradiance in collector plane falls down as the global incident in collector plane increases and it reaches to zero when the global incident reaches the maximum value 1200 W/m^2.

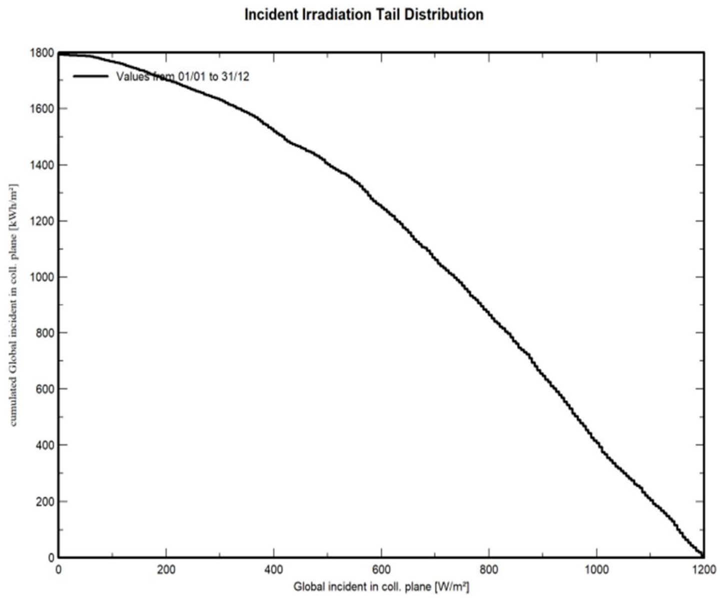

Fig. 18 Incident Irradiation Tail Distribution

5) *Array Temperature vs Effective Irradiance:* The available power generated by PV array output (PDC) depends on the solar irradiance and temperature of the PV site installation. So, it is very important to know the geographical distribution of the solar irradiation level and the operating temperature condition at the specific site before PV installation is implemented. A scatter plot in figure 19 indicates a linear relationship between the in-plane solar irradiance with the operating PV module temperature. Within one year period's data was observed, it is concluded that the highest solar irradiance was approximately 1900 W/m2 occurred during the month of January 2012 with the maximum operating PV module temperature recorded about 95°C as described below.

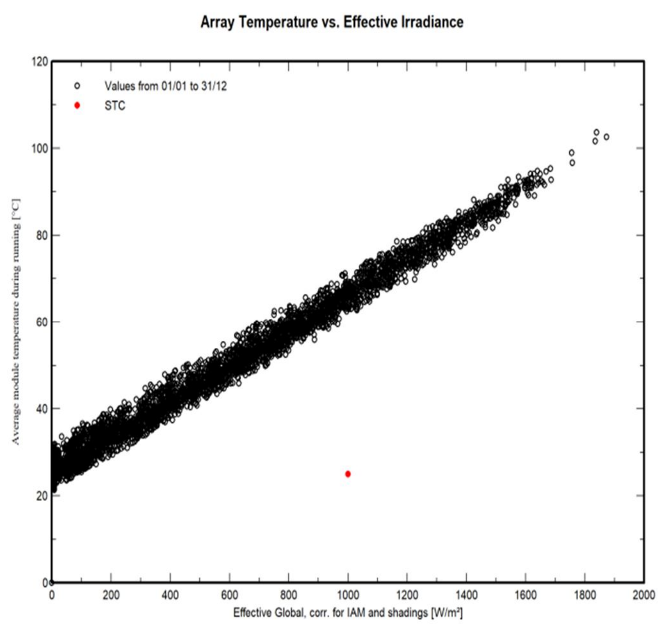

Fig. 19 The relationship between operating PV module temperature and in- plane solar irradiance in 2012

6) *Daily Input/output Diagram:* The figure 20 presents the Input/output diagram which gives detailed information about the general specification of the PV system and represents the simulation of every day of the energy that was generated in the correlation with the global incident irradiation over the photovoltaic panels. Each point of the graph represents the production of one day. The x-axis represents the daily irradiation in the collector plane [kWh/m^2/day], while the y-axis represents the system's production [kWh/day]. There is a small dispersion of points that could be explained by a high irradiation hitting the panel surface; resulting to increase of the energy delivered of PV system.

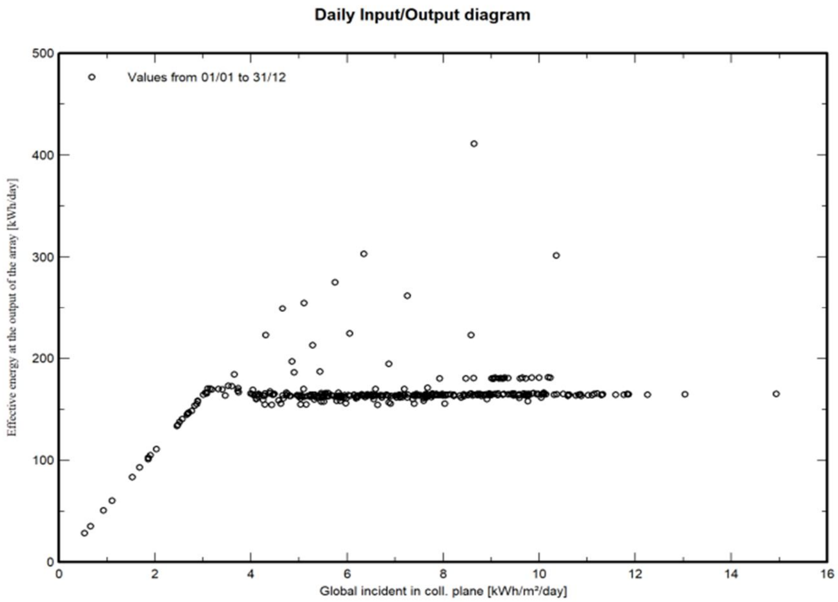

Fig. 20 The Input/output diagram of the designed system

IV. CONCLUSION

This paper has clearly shown the procedure for the optimization of solar panel orientation (tilt and azimuth angle) for higher energy production, better system performance, lower system losses, and low operational cost; in a typical rural community to advance rural electrification. The system optimization and simulation was carried out with the "PVsyst simulation software" and it was based on: fixed tilted plane (yearly irradiation yield). This optimization technique eliminates the stress, challenges, and inconveniences associated with changing the solar panel orientation every season for best solar irradiation or using the expensive and inefficient sun tracker in tracking sun energy. The PVsyst simulation software is designed to be used by architects, engineer and researchers for the study, sizing, optimization, simulation, configuration, energy prediction, and data analysis of complete PV system (whether standalone or grid connected). As clearly shown in this paper, the optimization parameters are strongly dependent on geographical site location and the meteorological data peculiar to the project location. During the optimization process, the best orientation for the solar panel was discovered at tilt angle of 40^0 and azimuth angle of 0^0. This installation angle of 40^0 tilt and azimuth angle of 0^0 gave the highest possible global on collector plane (solar irradiation) of 1629Kwh/m^2, with 0.0% loss with respect to optimum as clearly shown in table 1: optimization table for different tilt/azimuth angle and their corresponding values. So at Ndikelionwu (a typical rural community in Nigeria), solar panel must be installed at tilt angle of 40^0 and azimuth angle of 0^0 for optimal performance and high energy production.

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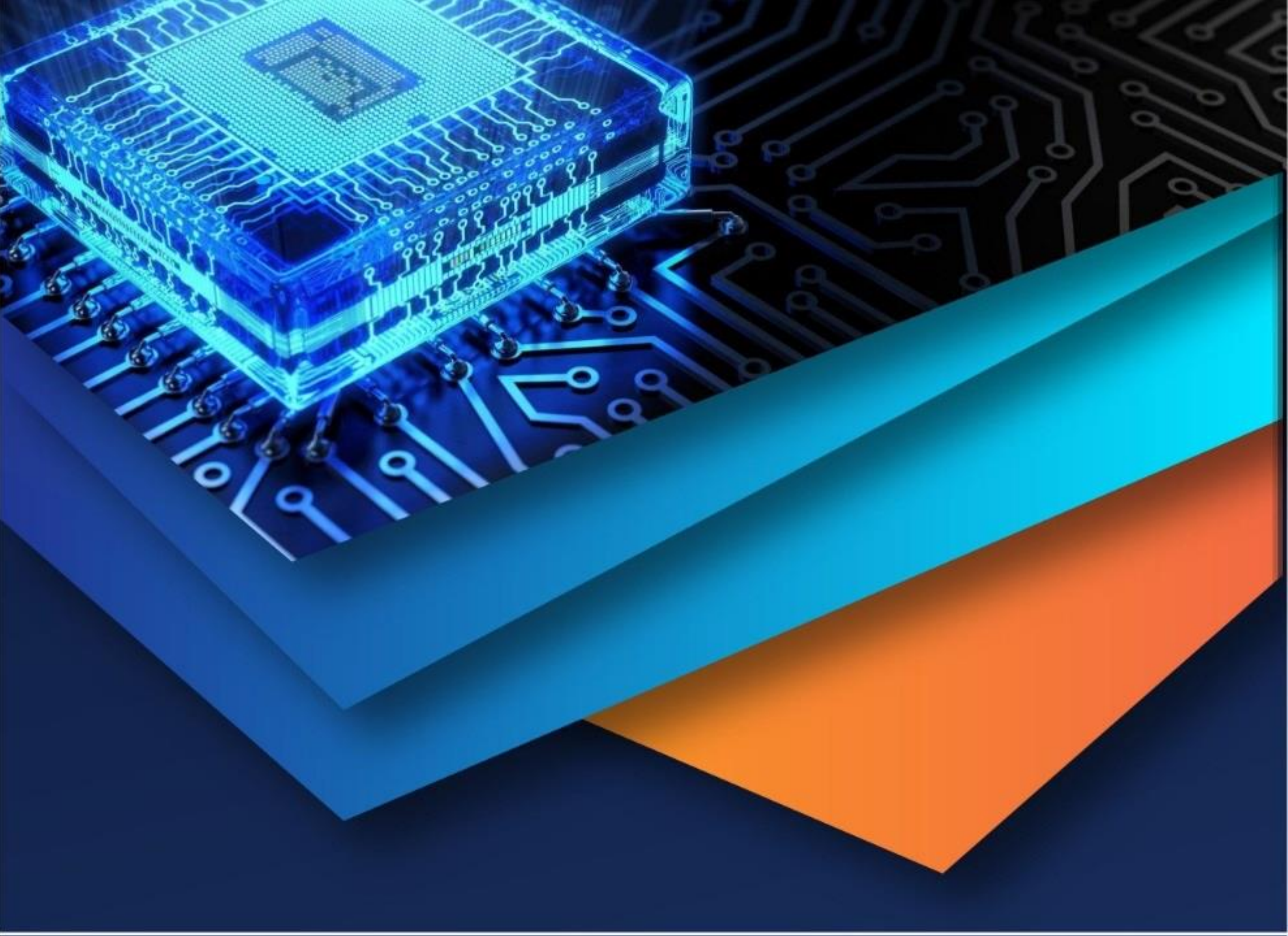

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