Nigerian Journal of Solar Energy, Vol. 26, 2015.

Solar Energy for Power Generation: A Review of Solar Radiation Measurement Processes and Global Solar Radiation Modelling Techniques

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Abstract *- Solar Energy is the cleanest and the most abundant renewable energy in the world. Solar radiation data are the most important resources needed for solar energy system design. Knowledge of the amount of available solar radiation in any location of interest is of prime importance to the solar energy design experts. This study examines the influence of atmospheric components on solar radiation passing through the earth's atmosphere. The intensity of solar radiation is attenuated as it passes through the earth's atmosphere. Also, methods of solar radiation measurement and the various empirical models for estimating global solar radiation in areas where such data are not available are presented. However, no method can be acclaimed to be the best as the performance of the models vary with location. Hybrid parameter based models have been reported to predict global solar radiation on horizontal surface with a high degree of accuracy in many locations in across the globe. Finally, two simulation tools for analysing solar power system were discussed. RETScreen software is majorly used for photovoltaic applications while HOMER includes additional renewable energy simulation features which make it suitable for analysing hybrid power system.*

Keywords: Solar Radiation, Meteorological data, Empirical models, Simulation models and HOMER

1.0 INTRODUCTION

The need for adequate and sufficient power generation to meet the energy need of the populace is a global issue. Power generation (Electricity supply) is of great concern either due to its inadequacy, as in the case of some developing countries, or the exhaustible nature of the conventional power sources and its associated environmental challenges. This has turned people's interest to renewable energy as a means of bridging the energy gap and providing environmentally friendly energy.

Solar Energy is the cleanest and the most abundant renewable energy in the world. Solar radiation data is the most important resource needed for solar energy system design. So the knowledge of the available solar radiation in any location of interest is of prime importance to a solar energy design expert. To generate electricity from solar energy, there is need to understand the spatial and temporal variation of solar energy on earth, and the factors responsible for such. Also, due to unavailability of solar radiation data in many locations, the solar energy system design expert must be familiar with the various models used to estimate global solar radiation so as to determine the amount of global solar radiation available at any location from the available meteorological parameters. Therefore, the focus of this paper is to address the above issues by: reviewing the processes of solar radiation transmission to earth, exploring some empirical models for estimating global solar radiation, as well as simulation models for solar power system design.

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2.0 BASICS OF SOLAR RADIATION

Solar radiation is the electromagnetic radiation emitted from the sun. The sun is the source of almost all the energy on earth. Solar energy therefore refers primarily to the light and radiant energy from the sun. The temperature of the sun decreases from a central value of about 5 x 10^6 K to about 5,800 K at the sun's surface. The source of solar energy is believed to be generated from the steady conversion of four hydrogen atoms to one helium atom in the interior of the sun with temperature up to many millions of degrees.

It is estimated that the sun radiates energy into space at the rate approximately 3.8 x 10^{20} MW (Smil, 1991). The earth intercepts only a small fraction of the energy ranging from the ultraviolet (UV) to the infrared (IR) in the wavelength range between 0.3 and 3.0 µm. The earth receives 174 petawatts (PW) of incoming solar radiation known as insolation at the upper atmosphere. Approximately 30% of this is reflected back to space while the rest is absorbed by clouds, oceans and land masses. The total solar energy absorbed by the earth's atmosphere, oceans and land masses is approximately 3,850,000 exajoules (EJ) per year (Smil, 2006). The modification of incoming solar radiation by atmospheric and surface processes is shown in Figure 1.

The solar radiation reaching the earth's surface has two components: direct and diffuse radiation. The sum of the two components (i.e. direct and diffuse solar radiation) is known as '**global solar radiation'**.

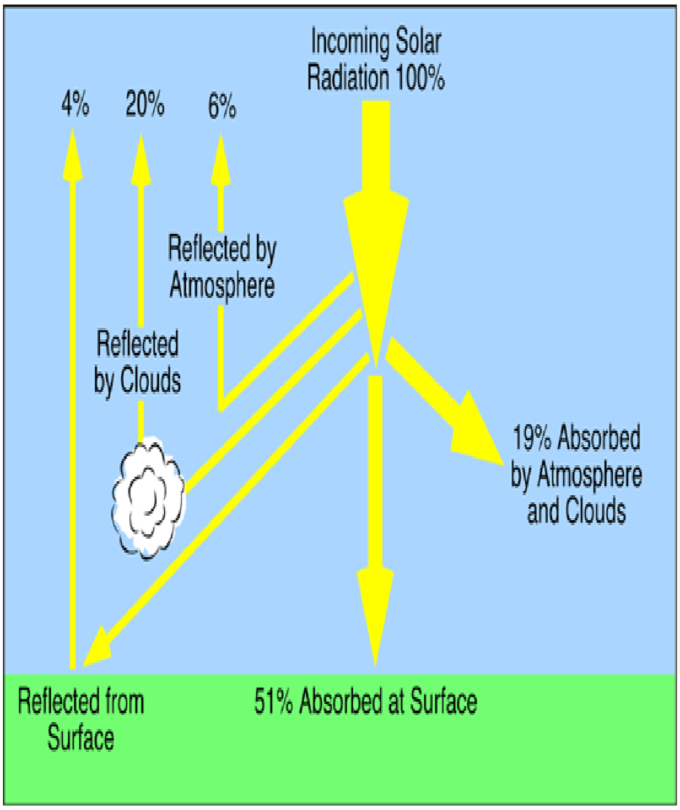

Figure 1: Modification of incoming global solar radiation by atmospheric and surface processes
Source: Pidwirny (2006).

Direct radiation is the solar radiation received by the earth's surface without being deflected/intercepted or absorbed by the atmosphere. The maximum beam (direct) radiation received at the surface of the earth at sea level on clear days is about 1000 Wm^{-2}.

Diffuse radiation is the solar radiation received by the earth's surface that is first intercepted by the atmosphere (i.e. clouds, dust particles, ozone and aerosols) and re-radiated to the ground.

Other terms associated with solar radiation are defined below:

Solar Constant: This is defined as the amount of solar energy received per unit time on a unit area of surface perpendicular to the radiation and at the outer limit of the atmosphere when the earth is at its mean distance from the sun. The value of the solar constant is approximately 1367 Wm^{-2}.

Solar Irradiation (Insolation): Is the solar radiation received at the earth's surface per unit area. It is measured in MJm^{-2} or Whm^{-2}.

Solar Irradiance: This is the rate at which solar energy reaches a unit area at the earth's surface. It is measured in watts per square meter (Wm^{-2}).

Extra-terrestrial Solar Radiation: This is the solar radiation received outside the earth atmosphere.

2.1 Factors Affecting Availability of Solar Energy on Earth

The intensity of the solar energy radiated to the earth is constant but the solar radiation is attenuated as it passes through the earth's atmosphere. The atmospheric medium through which the solar radiation passes contains variable amount of components such as gases, water vapour (cloud), aerosols and dust particles which act as a dynamic filter by absorbing, reflecting and scattering the solar radiation.

Absorption of solar radiation is the process in which solar radiation is retained by a substance (which intercepts it) and converted into heat energy. Atomic and molecular oxygen and nitrogen absorb very short wave radiation, effectively blocking radiation with wavelengths <190 nm. Ozone strongly absorbs longer wavelength ultraviolet in the Hartley band from 200 - 300 nm, and weakly absorbs visible radiation. Water vapour, carbon dioxide and, to a lesser extent, oxygen selectively absorb in the near infrared. Some of the absorbed energy is re-radiated in the far infrared.

Reflection of solar radiation occurs when an incident radiation is redirected back to space after striking an atmospheric particle. Reflection causes hundred percent loss of the insolation as the sunlight is redirected by 180^0 after it strikes a particle in the atmosphere. Cloud is responsible for most of the reflection that occurs in the earth's atmosphere. The proportion of solar radiation reflected depends on the particle reflectivity or 'albedo'. The reflectivity of a cloud can range from 40-90% (Pidwirny, 2006).

Scattering of solar radiation occurs when small particles (such as aerosols and dust particles) and gas molecules in the atmosphere diffuse part of the incoming radiation in random directions without any alteration to the wavelength of the electromagnetic radiation. Light is scattered differently in the atmosphere depending upon its wavelength, and this results in the blue sky during the day because this colour corresponds to those wavelength that are best diffused. Also, the sky appears red in colour at sunrise and sunset because lower wavelength (higher energy) light is more effectively absorbed and scattered as the solar radiation travel through a longer path length.

In general, the amount of solar radiation reaching the earth's surface varies greatly because of changing atmospheric conditions and the changing position of the sun. The variation of solar radiation with respect to location, time of the day and season of the year are explained below.

2.1.1 Variation of Solar Radiation with Location

The intensity of solar radiation received at the earth's surface decreases from the equator to either pole. The intensity is high at the equator with latitude 0^0, and least at the poles with latitude of 90^0. Regions close to the equator have high solar energy potential compared to regions around either pole because of their closeness to the sun (resulting from the spherical shape of the earth). However, the region lying between 15^0 and 35^0 latitude north and south respectively receives higher yearly sunshine hours than region in the equatorial belt from 15^0N to 15^0S. This is due to the fact that region lying between 15^0 and 35^0 latitude have relatively little rains and clouds such that over 90% of the incident sunshine is direct radiation while the region lying 15^0N to 15^0S have high humidity and frequent clouds which result in a high proportion of diffuse radiation. Also, the cold polar-regions do not get high sun because the Earth is spherical in shape, and as a result of the tilted axis of earth's rotation, these regions receive no sun for every month of the year.

2.1.2 Variation of Solar Radiation with Time of the Day and Season of the Year

The rotation of the earth about its polar axis causes day and night; the tilt of this axis relative to the ecliptic plane produces our seasons as the earth revolves about the sun. The earth rotates on its axis with a period of approximately 24 hours; hence sunlight is available for only an average of 12 hours a day. The amount of the solar radiation received on earth's surface varies with the time of the day as a result of the changing position of the sun. The ground level spectrum also depends on how far the sun's radiation must pass through the atmosphere. At any location, the length of the path the radiation must take to reach ground level changes as the day progresses. So not only are there the obvious intensity changes in ground solar radiation level during the day, going to zero at night, but the spectrum of the radiation changes through each day because of the changing absorption and scattering path length. On a clear day, solar insolation reaching the earth's surface increases from early morning to a peak at midday and then decreases to zero at night. At midday, the sun is overhead and its path length is shortened. Consequently, less solar radiation is scattered or absorbed, and more direct radiation reaches the earth's surface compared to any other time of the day

3.0 SOLAR RADIATION DATA

Solar radiation data at any location of interest can be collected by installing measuring instruments such as pyranometer and pyrheliometer at such place to monitor and record its day-to-day values. Pyranometer is used to measure global solar irradiance, while pyrheliometer is used to measure the direct normal component of the solar irradiance. However, lacks of measuring instruments and techniques involved, and poor maintenance culture especially in developing countries, have led to unavailability of solar radiation data (Agbo *et al*., 2010). For instance, in Nigeria, solar radiation data are mainly measured by Nigeria Metrological Agency (NIMET) at all the airports across the country. The limited coverage of this measurement indicates that solar radiation data are not readily available for many locations in the country; hence there is a need to employ theoretical methods for estimating solar radiation at any required location. In view of this, several empirical models have been developed to estimate the global solar radiation in locations where such data are not available, using some meteorological parameters such as: sunshine duration, air temperature, cloud cover, precipitation, relative humidity, e.t.c.

3.1 Models for Estimating Solar Radiation

Over the years, many models have been proposed to predict the global solar radiation in locations where the measured values are not available, using various meteorological parameters recorded at such sites. The number of correlations published and tested to estimate global solar radiations is relatively high, which makes it difficult to select the best method for a particular site and purpose. Besharat *et al*., (2013) classified various global solar radiation models available in the literature into four categories based on the meteorological parameters employed as model input (i.e. Sunshine-based, Cloud-based, Temperature-based, and Hybrid-parameter based models).

However, sunshine duration, cloud cover and temperature are the most widely and commonly used among the various meteorological parameters, to predict global solar radiation and its components. Some of the proposed models for predicting global solar radiation can be used in different regions and climates, while others contain empirical coefficients that are site-dependent. So there is the need to calibrate the empirical coefficients against the local data first when used in locations other than its base region. Some of the models under the classification stated above are hereby discussed.

3.1.1Sunshine-based models

Sunshine duration is the most commonly used parameter for estimating global solar radiation. Sunshine-based models are commonly used probably for the ease of obtaining reliable sunshine data that are widely available at most weather stations. Some of the models that employ sunshine ratio in estimating global solar radiation are presented below.

3.1.1.1 Angstrom–Prescott model

The first model for estimating the monthly average daily global solar radiation was proposed by Angstrom in 1924. The proposed relation was deduced based on a correlation between the ratios of average daily global radiation to the corresponding value on an entirely clear day. Prescott (1940) modified the Angstrom relation with a view to resolving the ambiguity characterizing the definition of the clear sky global solar radiation. The modified version is known as Angstrom-Prescott model. Angstrom-Prescott model is the most widely used correlation for estimating monthly average daily global solar radiation. Almost all the other sunshine based models are modifications of the Angstrom-Prescott model. The Angstrom-Prescott model is given as:

$$\frac{H}{H_O} = a + b\frac{S}{S_O} \qquad (1)$$

The values of H_o can be calculated using the equation given by Duffie and Beckman, 1991 as:

$$H_O = \frac{24\times3600}{\pi} \times I_{SC}\left[1.0 + 0.033cos\left(\frac{360dn}{365}\right)\right] \times \left[cos\emptyset cos\delta sin\omega_S + \frac{\pi}{180}\omega_S sin\delta sin\emptyset\right] \qquad (2)$$

where:

ω_s = Sunset hour angle in degree defined as:

$$\omega_s = \cos^{-1}(-\tan\emptyset\tan\delta); \qquad (3)$$

δ = declination angle given as:

$$\delta = 23.45\sin[360(284 + dn)/365]; \qquad (4)$$

$\emptyset$ = the latitude of the location;

dn = day number of the year starting from the first of January;

I_{SC} = Solar constant given as 1367 (Wm^{-2});

H = monthly average daily global radiation on a horizontal surface ($MJm^{-2}day^{-1}$);

H_O = monthly average daily extraterrestrial radiation on a horizontal surface;

S = monthly average daily number of hours of bright sunshine;

S_O = monthly average daily maximum number of hours of possible sunshine given as

$$\left(S_O = \frac{2}{15}\omega_S\right); \qquad (5)$$

a, b = the regression constant to be determined and can be obtained from the relationship given as (Tiwari and Sangeeta, 1977):

$$a = -0.110+0.235\cos\emptyset+0.323(S/S_O) \qquad (6)$$

$$b = 1.449-0.553\cos\emptyset-0.694(S/S_O) \qquad (7)$$

3.1.1.2 Page Model

Page presented a modified form of Angstrom-Prescott model with coefficients which he claimed to be applicable anywhere in the world (Page, 1961):

$$\frac{H}{H_O} = 0.23 + 0.48\left(\frac{S}{S_O}\right) \qquad (8)$$

3.1.1.3 Rietveld Model

Rietveld proposed a unified correlation for estimating global solar radiation on a horizontal surface by using measured data collected from 42 stations across different countries of the world. Rietveld's model is acclaimed to be applicable anywhere in the world. Rietveld's model is expressed as follow (Rietveld, 1978):

$$\frac{H}{H_O} = 0.18 + 0.62\left(\frac{S}{S_O}\right) \qquad (9)$$

Rietveld also examined several published values of a and b coefficients of the Angstrom–Prescott model and noted that constants a and b are related linearly to the appropriate mean value of S/S_o as follows (Rietveld, 1978):

$$a = 0.10 + 0.24\left(\frac{S}{S_O}\right) \qquad (10)$$

$$b = 0.38 + 0.08\left(\frac{S}{S_O}\right) \qquad (11)$$

3.1.1.4 Ogelman *et al*. model

Ogelman *et al*., (1984) developed a second order polynomial equation for estimating global solar radiation from sunshine duration as follow:

$$\frac{H}{H_O} = a + b\left(\frac{S}{S_O}\right) + c\left(\frac{S}{S_O}\right)^2$$

$$\frac{H}{H_O} = 0.195 + 0.676\left(\frac{S}{S_O}\right) - 0.142\left(\frac{S}{S_O}\right)^2 \qquad (13)$$

3.1.1.5 Newland Model

Newland proposed a linear-logarithmic model, which he used to obtain the best correlation between the ratio of global to extraterrestrial radiation and the sunshine duration ratio (Newland, 1988):

$$\frac{H}{H_O} = a + b\left(\frac{S}{S_O}\right) + clog\left(\frac{S}{S_O}\right) \qquad (14)$$

$$\frac{H}{H_O} = 0.34 + 0.40\left(\frac{S}{S_O}\right) + 0.17log\left(\frac{S}{S_O}\right) \qquad (15)$$

3.1.2 Cloud-based models

In the absence of sunshine data, cloud-based models can be a useful alternative but are sensible to human biasing (Supit and Van Kappel, 1998; Badescu, 1999). Two examples of correlations which use only cloud cover as input parameter are presented below:

3.1.2.1 Black Model

Black developed quadratic equation for the correlation of ratio of global to extraterrestrial radiation with average total cloud cover using data from different parts of the world (Black, 1956):

$$\frac{H}{H_O} = 0.803 - 0.340C - 0.458C^2 \quad C \leq 0.8) \quad (16)$$

where C is average total cloud cover during day time observations (octa).

3.1.2.2 Badescu Model

Badescu (1999) proposed a cloud-based model based on a correlation between the clearness index and the mean total cloud cover during daytime observations of the form:

$$\frac{H}{H_O} = a + bC \quad (17)$$

where, a *and* b are regression coefficients, while C is the mean total cloud cover during daytime observations (octa). The calibration results of the Badescu model for some selected location in Nigeria showed a high degree of accuracy (Okundamiya *et al*., 2015).

3.1.3 Temperature-based models

Air temperature is a commonly available measured parameter in many meteorological stations. Hence, several empirical models using air temperature as their input parameter have been proposed for estimating global solar radiation. This temperature based models assume that the difference in maximum and minimum temperature is directly proportional to the fraction of extraterrestrial radiation received at the ground level. Some of these models are presented below:

3.1.3.1 Hargreaves and Samani Model

Hargreaves and Samani **(**1982) were the first to propose a procedure to estimate the global solar radiation by using the difference between daily maximum and daily minimum air temperature and extraterrestrial irradiation. The proposed equation has the following form:

$$\frac{H}{H_O} = a(T_{max} - T_{min})^{0.5} \quad (18)$$

The coefficient a was initially set to 0.17 for arid and semi-arid regions. Hargreaves (1994) later recommended using a = 0.16 for interior regions and a = 0.19 for coastal regions.

3.1.3.2 Bristow and Campbell Model

Bristow and Campbell proposed an exponential model for estimating daily global solar radiation from the difference between daily maximum and daily minimum air temperature in the form (Bristow and Campbell, 1984):

$$\frac{H}{H_O} = a[1 - exp(-b\Delta T^c)] \quad (19)$$

where, ΔT is the temperature term difference. Although coefficients a, b and c are empirical, they have some physical meaning. Coefficient a represents the maximum radiation that can be expected on a clear day, while coefficients b and c control the rate at which a is approached as the temperature difference increases.

3.1.3.3 Goodin *et al*. Model

Goodin *et al*., (1999) refined the Bristow and Campbell model by adding an H_o-term meant to act as a scaling factor allowing ΔT to accommodate a greater range of H values:

$$\frac{H}{H_O} = a\left[1 - exp\left(-b\left(\frac{\Delta T^c}{H_O}\right)\right)\right] \quad (20)$$

The results proved that this model provides reasonably accurate estimates of irradiance at non-instrumented sites and that the model can successfully be used at sites away from the calibration site (Besharat *et al*., 2013).

3.1.4 Hybrid Parameter Based Models

The hybrid parameter based model used a combination of meteorological parameters such as relative humidity, soil temperature, dew point temperature, air temperature, precipitation, pressure, sunshine duration etc. in predicting global solar radiation. It is reported that hybrid parameter-based model predicts the solar radiation on a horizontal surface with a high degree of accuracy (Supit and Kappel, 1998), but most of their input parameters are not readily available at most locations of interest (Besharat *et al*., 2013; Okundamiya *et al*., 2015).

3.1.4.1 Swartman and Ogunlade Model

Swartman and Ogunlade (1967) expressed global solar radiation as a function of relative sunshine and relative humidity (RH) as:

$$\frac{H}{H_O} = a + b\left(\frac{S}{S_O}\right) + cRH \quad (21)$$

where, a *and* b are regression coefficients, while *RH* is the monthly average daily relative humidity (%).

3.1.4.2 Ojosu and Komolafe Model

Ojosu and Komolafe developed correlations between global solar radiation and three meteorological parameters (sunshine hour, air temperature and relative humidity) in the form (Ojosu and Komolafe, 1987):

$$\frac{H}{H_O} = a + b\left(\frac{S}{S_O}\right) + c\left(\frac{T_{min}}{T_{max}}\right) + d\left(\frac{RH_{min}}{RH_{max}}\right) \quad (22)$$

where *T*max, *T*min, *RH*max, and *RH*min are the mean maximum air temperature, mean minimum air temperature, mean maximum relative humidity, and mean minimum relative humidity, respectively.

3.1.4.3 Okundamiya model

Okundamiya developed correlations between global solar radiation and other meteorological parameters based on monthly average daily data sets collected for different locations in Nigeria and proposed a relation of the form:

$$\frac{H}{H_O} = a + b\left(\frac{S}{S_O}\right) + c\left(\frac{T_{min}}{T_{max}}\right) + dT_{max} + eC \qquad (23)$$

where, *a*, *b*, *c*, *d and e* are regression coefficients. Okundamiya *et al*., (2015) applied this model alongside five other models to estimate the global solar radiation on a horizontal surface in some selected locations in Nigeria and found that the model has the overall best accuracy with the least RMSE and MABE (≤ 1.0854 and 0.8160 $MJm^{-2}day^{-1}$ respectively), and least monthly relative percentage error (< ± 12%) for the entire sites.

4.0 SOLAR POWER GENERATION

Solar power is the conversion of sunlight into electricity, either directly using photovoltaic (PV) or indirectly using concentrated solar power (CSP). CSP systems use lenses or mirrors and tracking systems to focus a large area of sunlight into a beam. PV converts light into electric current using the photoelectric effect (Martin and Goswani, 2005). Solar energy conversion offers great potential in meeting future global energy need. Unlike other energy sources, solar power generation is a silent, clean, inexhaustible energy source. Globally, the percentage of solar electricity produced from PV systems is greater than that from CSP. According to the national renewable energy action plan (NREAP) presented by the member states of the European Union (EU), 82% of solar electricity in 2020 in the EU is aimed to be generated with photovoltaic (PV) systems, while the remaining 18% will be derived from concentrated solar power plants (Monforti *et al*., 2014). Some advantages of PV power system are as follows:

i. It requires little maintenance
ii. It is modular and can be quickly installed
iii. It can be more easily expanded as demand increases
iv. It can be generated where it is required without the need for transmission line.

5.0 SIMULATION MODELS FOR SOLAR POWER SYSTEM

Several computer simulation models have been developed for the analysis of solar power system. These softwares are very useful in the design of solar power project and perform specific tasks which vary from one model to another. Two of such simulation tools are discussed below.

5.1 HOMER (Hybrid Optimization Model for Electric Renewable)

Homer is a computer model that simplifies the task of evaluating design options for both off-grid and grid connected power systems for remote, stand-alone and distributed generation (DG) applications. It has been developed by United States (US) National Renewable Energy Laboratory (NREL) since 1993. It is developed specifically to meet the needs of renewable energy industry's system analysis and optimization. There are three main tasks that can be performed by HOMER: simulation, optimization and sensitivity analysis. In the simulation process, HOMER models a system and determines its technical feasibility and life cycle. In the optimization process, HOMER performs simulation on different system configurations to come out with the optimal selection. In the sensitivity analysis process, HOMER performs multiple optimizations under a range of inputs to account for uncertainty in the model inputs (Abdulqadiri and Elwan, 2012). HOMER is used for designing and analyzing hybrid power systems, which contain a mix of conventional generators, cogeneration, wind turbines, solar photovoltaics, hydropower, batteries, fuel cells, hydropower, biomass and other inputs.

5.2 RETScreen Software

The RETScreen International Clean Energy Project Analysis Software is unique decision support tool developed with the contribution of numerous experts from government, industry, and academia. The software, provided free-of-charge, can be used worldwide to evaluate the energy production and savings, life-cycle costs, emission reductions, financial viability and risk for various types of energy efficient and renewable energy technologies (RETs). RETScreen software can be used for three basic PV applications: on-grid; off-grid; and water pumping. For on-grid applications, the model can be used to evaluate both central grid and isolated-grid PV systems. For off-grid applications, the model can be used to evaluate both stand-alone (PV-battery) and hybrid (PV/battery/genset) systems. For water pumping applications, the model can be used to evaluate PV-pump systems.

The software can model a wide variety of projects ranging from large scale multi-array central power plants, to distributed power systems located on commercial buildings and houses, to industrial remote wind-PV-genset hybrid power supplies. The software is available in multiple languages. It also includes product, project and climate databases, and a detailed user manual (RETSrceen, 2015).

6.0 CONCLUSION

The intensity of solar radiation at a particular location is influenced by the atmospheric factors of that environment since solar radiation is attenuated as it passes through the earth's atmosphere. A brief overview of some of the available models for global solar radiation is provided in this work. No method can be acclaimed to be the best as the performance of the models vary with location. Although, the Angstrom type models have been widely used with high degree of accuracy in many locations, hybrid parameter-based models have been reported to predict global solar radiation on horizontal surface with a high degree of accuracy in many locations across the globe. There is need to test some of the available models in various locations to determine the most suitable for any particular environment. Simulation models are employed in analysing solar power system. RETScreen software is majorly used for photovoltaic applications while HOMER includes additional renewable energy simulation features. This makes HOMER software the most widely used software for analysing the hybrid power system.

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