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Modelling of hourly solar radiation collected on a tilted surface at Banket in Mashonaland West, Zimbabwe for optimum design of off-grid solar systems.

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Abstract

Off-grid solar systems have become the most viable means of bringing electricity to sparsely populated rural communities of sub-Saharan Africa. This mostly because of the sharply falling prices of solar equipment and the maturity of the technology. The solar systems are also modular thus can be deployed at variety capacities for different applications. Zimbabwe has abundance solar resources ubiquitously spread country over. The design of the systems has however, been based on average country radiation which usually under-estimate or overestimate the insolation at a given site. This therefore affects the sizing of the systems and thus the cost. Also for off-grid systems it is not economical to carryout data collection of at least a year, which is another way to get accurate data. This study resorted to satellite data available on a freely accessible EU site as Typical Meteorological Year Data of 2009 downloaded using the Banket coordinates. The TMY data was used as the input to the model where, radiation data was input into the mathematical model of the tilted plane by Collares-Perreira and Rabl of 1996. Feeding the horizontal, beam and diffuse radiation data plus the ambient temperature into mathematical models resulted in the calculation of the solar radiation that can be received on a plane tilted at an angle equal to the latitude of the place. The data plotted for the whole year is a closer representative of the distribution of radiation received at the site for the whole year and thus reliable input to the design of off-grid solar systems as literature can confirm.

Key Words: Off-grid, Tilted plane, Radiation, Typical Meteorological Year (TMY).

1. Introduction

Renewable energy off-grid systems is the way to go to improve clean energy access in in Zimbabwe and the rest of all Sub-Saharan countries (Ouedraogo, 2017). This becomes more relevant as a way of providing a more independent energy pathway that transition from

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dependence on external resources (Mariaud, , et al., 2017). With the abundance of solar resource in sub-Saharan Africa and Zimbabwe in particular coupled with the falling solar Photovoltaic prices, solar PV off-grid systems become the most favored (Ye, Rodrigues and Lin, 2017). The other advantages of solar off-grid systems over other renewable include their modularity which brings flexibility and allow for ramping up approach (Hassan, Cipcigan and Jenkins, 2017). As long as additional hardware constraints are satisfied, PV generation and battery storage capacity can be increased to meet the growing needs of first time electricity customers (Korkovelos et al., 2020).The solar PV off-grid solutions come in different packages, ranging from pico-systems for lighting only, micro-systems (solar home systems) to the mini-grids that connect a number of homes and social facilities (Micangeli et al., 2020).

1.1 Application of Solar off-grid systems

Solar off-grid systems can be deployed for energy access for different applications. For example, solar off-grid systems can be applied as direct connections for example in solar water pumps for irrigation or drinking water supply (Zhou and Abdullah, 2017; Riva et al, 2018; Okpokam, 2021). Apart from direct coupling systems, solar off-grid systems are also installed as solar home systems to supply electricity for lighting, entertainment and other low demand applications. These can also be termed stand-alone systems(Akinyele, Belikov and Levron, 2017; Zhang et al., 2017). The systems do not usually exceed 500W (Bloomfield, Roberts and Cotterell, 2016; Avila et al., 2017). Systems up to 1kWwhich provide for a higher tier of energy access that is including supply to refrigerators, freezers and other reactive loads at small scale are called micro-grids (Booth et al., 2018). A higher tier for productive use energy needs larger systems above 1kW these are called mini-grids (Madhura et al, 2021). Mini-grids can provide electricity for a community of households coupled with business centres, clinics with reactive loads like grinding mills and other processing industry equipment (Contejean and Verin, 2017; Terrapon-Pfaff et al., 2018; Hartvigsson et al., 2021). For design of these systems, solar resource data for the location of the system is very crucial (Connolly et al., 2015; Zhou and Abdullah, 2017).

1.2 Solar Resource

Though not equally distributed, solar radiation is abundant and ubiquitous thus the resource can be tapped almost everywhere in the whole of Sub-Saharan Africa including Zimbabwe (Okpokam, 2021). For one to design a reliable solar system at any given location, reliably ground measured long term data, say above ten years, is required (Hove, Manyumbu and Rukweza, 2014). In Zimbabwe like many more developing countries, ground measured solar radiation data is available at a few sparsely populated stations which may not be a true representative of solar radiation received at a particular place of interest (Hove, Manyumbu and Rukweza, 2014). Limited stations are available for solar and other weather data in Zimbabwe thus a lot of interpolation needs to be done for most of the sites (Lim, 2011; Bhattacharyya and Palit, 2016; Mariaud, Acha, Ekins-Daukes, et al., 2017). This means high variability from representative data (Cebecauer and Suri, 2015). Accuracy of ground measured data is also dependent on the condition of the measuring instruments which may include cleanliness from dust and calibration together with age which may result in significant errors (Duffie and Beckman, 2013; Hove, Manyumbu and Rukweza, 2014; World Bank and Government of Zimbabwe, 2017). Nowadays satellite measured data has become another source of radiation data (Hove and Göttsche, 1999; Perez et al., 2013; Hove, Manyumbu and Rukweza, 2014). Though satellite data is more continuous it does not accurately represent solar radiation received at ground level (Nagpal and Parajuli, 2019). Satellite data is measured at the top of the atmosphere and thus require models to correlate the data to ground level

(Munawwar, 2006; Angenendt et al., 2016; Muhammad and Kabir, 2018). An improved approach is therefore to correlate satellite derived data with the sparsely ground measured data like what was done when developing the solar radiation map for Zimbabwe by (Hove and Göttsche, 1999) and was later updated by Hove, Manyumbu and Rukweza in 2013 (Hove, Manyumbu and Rukweza, 2014). The data used for construction of this map is monthly averages (Hove, Manyumbu and Rukweza, 2014).

To make satellite data more representative of the place's meteorological conditions, the data providers in the developed world are developing what is called a Typical Meteorological Year (TMY) data (Cebecauer and Suri, 2014, 2015). TMY is a set of meteorological data with data values for every hour in a year for a given geographical location. The data are selected from hourly data in a longer time period, normally ten years or more. For each month in a year, the data have been selected from the year that was considered most "typical" for that month (Cebecauer and Suri, 2015).

The solar radiation data, both satellite derived and ground measured is normally available as data measured on a horizontal plane. For designing of solar application systems and determination of their performance, a tilted plane is used. This means therefore that we need to determine solar radiation received on a tilted plane at a particular location and time. There are a number of models developed by different writers to derive the radiation received on a tilted plane. These models are mainly classified into isotropic and anisotropic tilted plane models (Duffie and Beckman, 2013).

Solar radiation received at a given location is highly dependent on the meteorological factors of the place (Alsharif, Nordin and Ismail, 2015; Bhattacharyya and Palit, 2016; Moner-Girona et al., 2016). These factors include ambient temperature which affects the cell operation temperature of the array (Notton, Lazarov and Stoyanov, 2010; Ben Othman, Belkilani and Besbes, 2018). The cell operation temperature has a bearing on the array efficiency (Alsharif, Nordin and Ismail, 2015; Stuart. and Escudero, 2017). Other meteorological aspects of concern are the location latitude, for inclination angle determination, longitude for calculation of solar time as well as the cloud cover which has an impact on the diffuse component of solar radiation (Hove and Chipfunhu, 2006; Yadav and Chandel, 2014; MacGill and Watt, 2015). Different methods are used to model the collected solar radiation data to radiation received on a tilted plane (Cimento, 1980; Hove and Chipfunhu, 2006; Kamali, Moradi and Khalili, 2006; Notton, Paoli and Diaf, 2013; Padovan *et al.*, 2014).

2. Methodology

The Typical Meteorological Year data for Banket, in Zimbabwe located on latitude: longitude coordinates of -17.4:30.4 was downloaded from an EU free site. The TMY data provided both hourly diffuse and global radiation components together with hourly ambient temperatures. Hourly radiation incident on a tilted surface is calculated from the Colleris-Pereira and Rubl sky model for the whole year.

2.1 Calculation of Average Hourly Radiation on a tilted plane

Radiation is normally given as daily data that is as daily global radiation on a horizontal plane, H_h. As stated by Duffie & Beckman, (2013), to solve the global radiation into its beam and diffuse component correlations of the ratio H_d/H_h with clearness index, $K = H_n/H_o$ are used.

Many correlations have been identified in the literature for different elements and location by different authors e.g. (Munawwar, 2006; Duffie and Beckman, 2013). Hove and Gotsle (1999) derived the following for Zimbabwe and the region (Hove and Chipfunhu, 2006; Hove and Tazvinga, 2012; Hove, Manyumbu and Rukweza, 2014);

$\frac{H_d}{H_h} = 1.0294 - 1.14K \; for \; K \leq 0.75$ and,

$= 0.175 \; for \; K > 0.75$

Where K is the clearness index and H_d and H_h are the daily diffusion and horizontal radiation. To resolve the daily value into hourly value factors r_d and r_h of Liu and Jordan (1996) and Collares Pereira and Rabl (1979) are used.

The factor, $r = \frac{I}{H}$

Where *I* is the hourly radiation and *H* is the daily radiation.

$r_d = \frac{I_d}{H_d}$; and $r_h = \frac{I_h}{H_h}$

Since *r* is a function of the hour angle *ω* and day length ω_s for diffuse radiation.

$$r_d = \left(\frac{\pi}{24} - \mathrm{Cos}\omega - \frac{\mathrm{Cos}\omega}{\mathrm{Sin}\omega_S - \omega}\right) * \mathrm{COS}\,\omega_S \qquad \textbf{Equation 2.1}$$

$$r_h = (a + b\cos\omega) r_d \qquad \textbf{Equation 2.2}$$

where a and b are correlation coefficients given by

a = 0,409 + 0, 5016 sin (ω s – 60) **Equation 2.3**

b = 0,6609 – 0,4767 sin (ω s-60) **Equation 2.4**

By adopting the Collares – Pereira and Rabl Sky Model and making some assumptions the instantaneous radiation incident on the array, *I*array can be estimated by

$$I_{array} = (I_h - I_d)\frac{\mathrm{Cos}\theta_{array}}{\mathrm{Cos}\theta_z} + I_d/c \qquad \textbf{Equation 2.5}$$

Where I_h is the global horizontal hourly radiation, θ array is the angle of incidence of direct irradiance on the array, c is the concentration ratio which is equal to unit for flat-plate array and I_d is the diffuse irradiance (Mongin, 1999; Anayochukwu and Onyeka, 2014; Gaurav *et al.*, 2015).

2.2 Geometric factor Rb

This represents the ratio of beam radiation on the tilted surface to that on a horizontal surface at any given time (Duffie and Beckman, 2013). This factor is important in the solar process design and performance calculations, as it is vital to calculate the hourly radiation on a tilted surface of a collector from estimates of solar radiation on a horizontal surface. The ratio, after some simplifications, is given by

$R_b = \cos\theta / \cos\theta_z$ **Equation 2.6**

where θz is the zenith angle, found in standard texts and is a function of the declination angle δ.

Declination Angle, δ

This refers to the angular position of the sun at solar noon and is found by

$$\delta = 23.45\sin[\frac{360}{365}(n + 284)] \qquad \textbf{Equation 2.7}$$

Where n is the day number in year of 365 days counting from the first day of January(Duffie and Beckman, 2013).

The angle of incidence, θ, as given in a number of standard texts,(Duffie and Beckman, 2013) can be determined from the following expression;

$$\cos\theta = \sin\delta\sin\Phi\cos\beta - \sin\delta\cos\varphi\sin\beta\cos y + \cos\delta\cos\varphi\cos\beta\cos\omega + \delta\sin\theta\sin\beta\cos y\cos\cos\omega + \sin\beta\sin y\sin\omega \qquad \textbf{Equation 2.8}$$

and; $\cos\theta = \cos\theta z\cos\beta + \sin\theta z\sin\beta\cos(\gamma s - \gamma)$ **Equation 2.8b**

This is the angle between the beam radiation on a surface and the normal to that surface (Duffie and Beckman, 2013).

Hour Angle (ω) is the angular displacement of the sun east or west of the local meridian due to rotation of the earth on its axis at 15^0 per hour, morning negative and afternoon positive(Duffie and Beckman, 2013).

The slope (β) refers to the angle between the plane at the surface in the practice when installing solar arrays is to place them at an angle β = latitude of location(Duffie and Beckman, 2013). **Zenith angle**, θz,is the angle between the vertical and the line to the sun, that is, the angle of incidence of beam radiation on a horizontal surface.

$$\cos\theta z = \cos\varphi\cos\delta\cos\omega + \sin\varphi\sin\delta \qquad \textbf{Equation 2.9}$$

The hourly solar irradiation incident on the PV array is a function of time of day, expressed by the hour angle; the day of the year; the tilt and azimuth of the PV array; the location of the PV array site as expressed by the latitude; as well as the hourly global solar irradiation and its diffuse fraction. The actual expression depends on the so-called sky model (a mathematical representation of the distribution of diffuse radiation over the sky dome) preferred. In this study, the simplified isotropic diffuse formula suggested by Collares-Pereira and Rabl (1979) was used because it can be applied with a simple data set that is easily obtainable in Zimbabwe.

$$I_{PV} = (I_h - I_d)R_b + I_d \qquad \textbf{Equation 2.3}$$

In Equation (2.3), I_h and I_d are, respectively, the hourly global and diffuse irradiation in W/m2. R_b is geometric factor representing the ratio of beam irradiance incident on a tilted plane to that incident on horizontal plane.

Hourly average meteorological data, global irradiation, diffuse irradiation and ambient temperature were used as inputs in evaluating Equations (2.1), (2.2) and (2.3) of the performance of the simulation model for the whole year. The evaluation was performed at the mid-point of each hour of the day, on every day of each month.

3. Results and Discussions

The irradiation data downloaded from the EU free site was analysed using the excel model developed basing on the Collaris, Perrera and Rabl sky model. The irradiation collected on a tilted plane at the location in Banket was calculated for all the days of the year as Ipv. This Ipv values is the input to evaluate power generated by a solar array installed at the current location for any given day of the year, Ppv.

3.1 Irradiation collected on a tilted plane on a given day

The calculated radiation incident on a tilted plane at an angle equal to the latitude of the site was plotted to give the graph below;

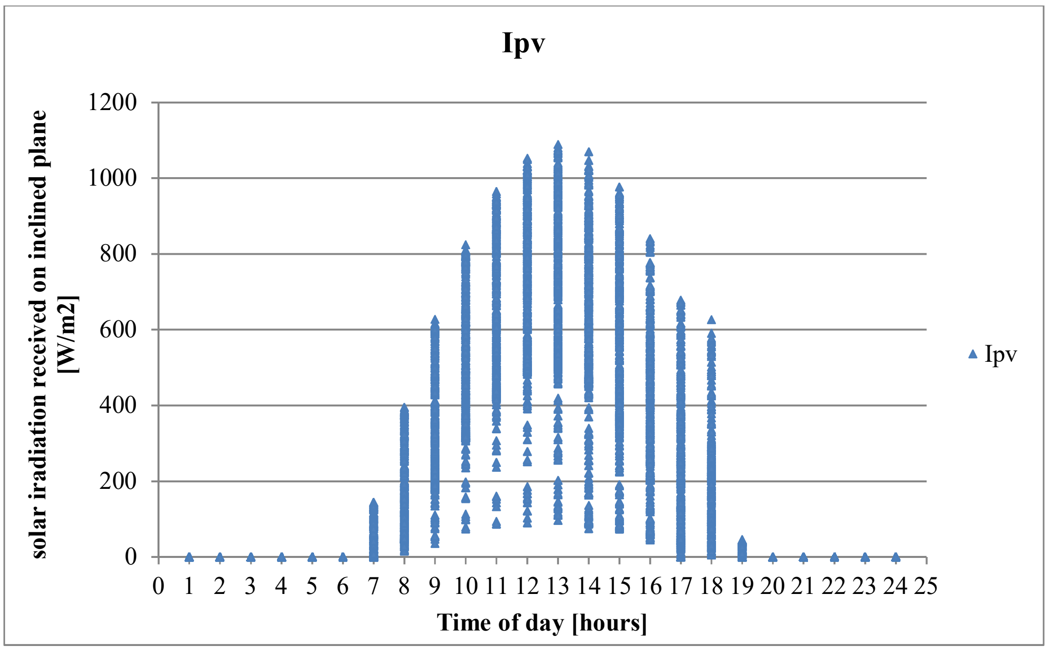

Figure 1: Irradiation collected on a tilted plane on a standard solar day

This shows that radiation received on a solar collector at Banket can reach a maximum of about 1500W/m2. An average of 1000W/m2 peak is reached between 1100hrs and 1500hrs, these are the peak generation hours on daily basis throughout the year. Inferring to literature, (Kamali, Moradi and Khalili, 2006) compared the different models Badescu (2002), Tian et al. (2001), Reindl et al. (1990), Skartveit and Olseth (1986), Koronakis (1986), Steven and Unsworth (1980), Hay (1979) and Liu and Jordan (1962) in evaluation of the tilted plane power collected. Reindl et al. (1990) model, was found to give more accurate results. The results therefore imply that Liu and Jordan, (1962) and the Clollaris Pereira and Rabl give acceptable results for adoption in the design of off-grid mini-grid systems.

3.2 Irradiation collected on a tilted plane during the year from January –December

Radiation collectable on a tilted plan at the site in Banket was modelled by excel based modelling tool. Figure 2 shows the distribution of the solar power incident on the tilted plane.

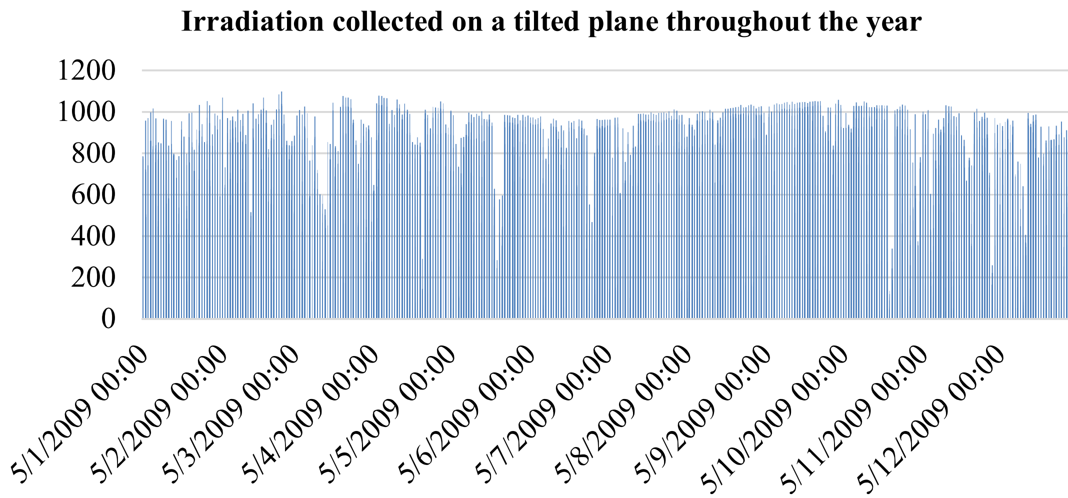

Figure 2: Irradiation collected on a tilted plane during the year

3.3 Power generated for a load profile of a randomly selected sample community in Banket

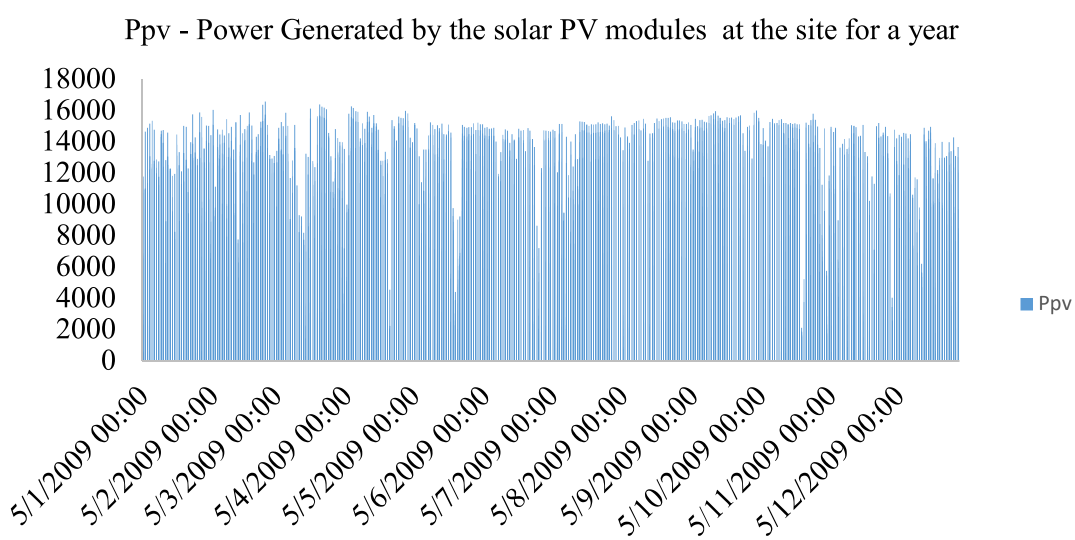

Figure 3: Power generated for a provided load profile

3.4. Comparison of the irradiation collected on a tilted plane at Banket and the power produced to meet a provided load profile for the location in Banket.

Depending on the load profile to be fed, the generator also produces to satisfy the load in accordance to the solar regime of the place as shown in Figure 4.

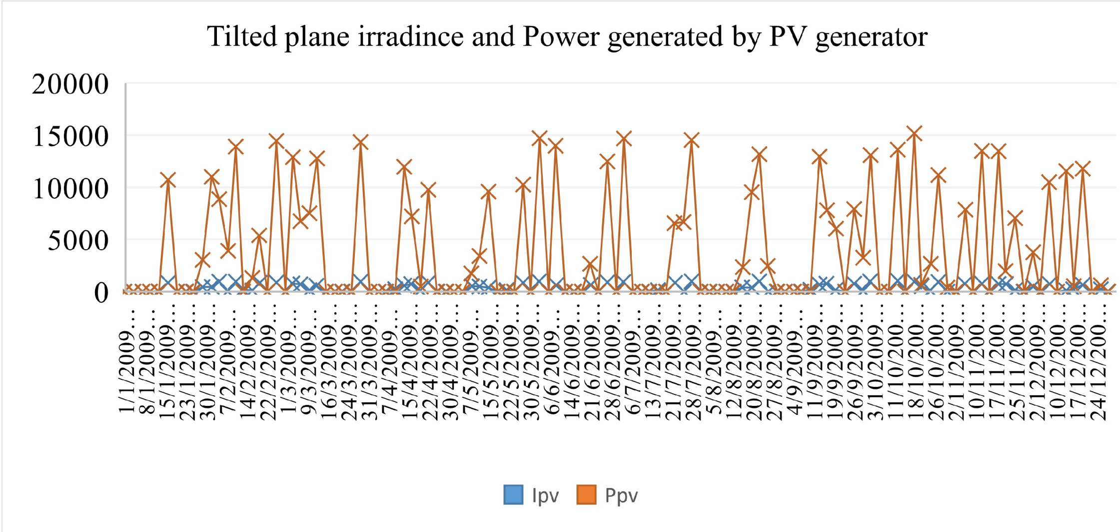

Figure 4: Comparison of solar radiation collected on titled plane to the power generated

The results indicate that the power produced is proportional to the radiation received by the panels tilted at an angle determined by the places latitude, thus the power produced is way higher than the radiation collected, this is highly influenced by the load profile of the location. Due to the modularity of solar systems, the system can be ramped up if other loads are to be introduced. The solar irradiation regime of a place is highly critical in sizing systems as this serves as the fuel of the power plant (Notton, Paoli and Diaf, 2013; Cebecauer and Suri, 2015; Ben Othman, Belkilani and Besbes, 2018).

3.4. Part of the Excel spread sheet used to analyse the solar radiation data

The excel based mathematical models used to analyse and model the tilted plane solar radiation received at Banket.

Table 4.1: Example of the excel model

Date&Time (UTC)	Dry bulb t	Relative Hu	Global ho	Direct (be	Diffuse hc	Infrared r	Windspe	Wind dire	Air press	HOUR[h]	day [n]	hour angl	declination a	Cosθz	θz	cosθ	Rb[cosθ/c	Ib	ih-id	Ipv	Load, L[wh/h	PV_EFFICIENCY	Ppv
1/1/2009 00:00	20.2	87.74	0	0	0	374.9	2.17	340	86936	1	1	-2.87979	-0.40162883	-0.73159	2.3914485	-0.91975	1.257193	0	0	0	795.20	0.17	0
1/1/2009 01:00	20.04	89.22	0	0	0	375.9	2.15	333	86930	2	1	-2.61799	-0.40162883	-0.64384	2.2703059	-0.82815	1.286261	0	0	0	795.20	0.17	0
1/1/2009 02:00	19.88	90.69	0	0	0	376.9	2.14	327	86924	3	1	-2.35619	-0.40162883	-0.50426	2.099316	-0.68243	1.353348	0	0	0	795.20	0.17	0
1/1/2009 03:00	19.73	92.17	0	0	0	377.9	2.12	321	86961	4	1	-2.0944	-0.40162883	-0.32234	1.8989991	-0.49253	1.527979	0	0	0	935.53	0.17	0
1/1/2009 04:00	19.57	93.64	0	0	0	378.9	2.1	316	86999	5	1	-1.8326	-0.40162883	-0.1105	1.6815221	-0.27139	2.456006	0	0	0	1091.46	0.17	0

The excel model shows sample inputs and results of the mathematical modelling of the solar data to the radiation received on a tilted plane and power generated by the PV generator sized to meet a load at the site. The results imply that mathematical models are the key to analysis of radiation data in sizing solar systems (Alsharif, Nordin and Ismail, 2015).

4. Conclusion

From the shape of the distribution of radiation over the hours of the day throughout the year is typical of any normal day from ground measured data. It was therefore concluded that for small solar systems like mini-grid and off-grid systems Typical Meteorological Year Data can be used as input to the designs without fear instead of ground measurements which may take time and can be costly. This can be faster and cheaper as compared to ground measured data which requires at least a year to give representative results. Locally developed solutions to data analysis for design of off-grid solar systems is more feasible in terms of costs.

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