The mapping of maximum annual energy yield azimuth and tilt angles for photovoltaic installations at all locations in South Africa

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Abstract

Photovoltaic (PV) technology is fast emerging as a viable energy supply option in mitigation against environmental degradation through the burning of traditional fossil fuels. The cost of the technology, however, still poses a major challenge, as the efficiencies are generally still quite modest. Current research efforts to improve efficiency are mainly focused on component physics and manufacturing technologies. Little attention seems to be paid to improved system design at field level. Traditionally it is assumed that a panel installed at a tilt angle that is equal to the latitude at a location should achieve maximum annual energy yield for a non-tracking installation. However, in practice, due to a number of factors such as wind speed, wind direction, air temperature, global and diffuse irradiation and other climatic factors, the optimum azimuth and tilt get more convoluted. In this paper the optimum angles (azimuth and tilt) to maximise annual energy yield for fixed angle PV installations at all locations in South Africa have been tabulated. Climate data software together with solar design software were used in determining the angles. The availability of these tables will offer an additional support tool to the country in promoting the growth of PV as a viable alternative energy generation technology for both urban as well as the most secluded rural areas that are not grid connected.

Keywords: photovoltaics, South Africa, tilt, azimuth

1. Introduction

South Africa is currently facing a range of energy related problems that include energy reliability, environmental sustainability and tariff hikes (Sebitosi *et al*., 2008; Sebitosi & Pillay, 2008; Sebitosi & Pillay 2008). The Department of Energy also identifies access for all to electricity as one of the primary goals of South Africa's energy policy. The need to integrate non-grid technologies into the Integrated National Energy Planning (INEP) as complementary supply-technologies to grid extension has been particularly highlighted (DME, 2003). Solar energy is a most readily accessible resource in South Africa and potentially offers an ample opportunity for alternative power generation that is also clean. In addition, there is a growing photovoltaic (PV) manufacturing sector in the country with annual panel-assembly capacity totalling 5MW. Despite this great potential, solar PV installations are still very expensive for ordinary users, more especially those in rural South Africa. Thus, this cost is one of the major limiting factors to the full utilization of PV technologies.

2. Motivation

Designing an installation to yield maximum annual energy helps to minimise the necessary installed capacity and reduce the cost of equipment. To achieve this, a generic solar collector must be mounted at right angles to the sun's rays. Ideally this is achieved by mounting the collector on a two-axis tracker that continuously tracks the sun by the hour and through the seasons. In practice, however, the method is quite cumbersome and inconvenient. Thus, the majority of installations are with fixed mountings. Figure 1 illustrates the reduction in solar intensity at location B that receives the sun at a smaller angle than location A.

Traditionally it is assumed that a collector that is mounted at a tilt angle that is equal to the latitude of a location, combined with an azimuth angle that is parallel to the equator, should achieve maximum annual energy collection. In the case of photovoltaics, however, the situation is more complicated.

A basic PV panel consists of several solar cells.

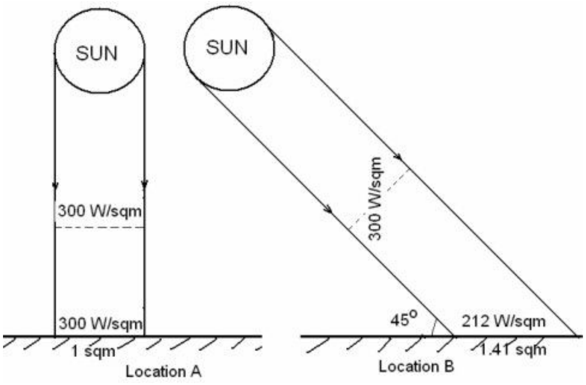

Figure 1: An illustration of the reduction of radiation intensity per square metre due to sun angle

Each solar cell can be modelled as a basic p-n junction, and hence the classic diode equation can be used in modelling outputs for the solar panel.

The diode equation is given by equation 1.

$$I = I_o(e^{\frac{qv}{kT}} - 1) \quad (1)$$

Where T is the temperature of the solar cell.

From this, various models for the electrical energy output of a PV panel have been derived. One such model is presented in (Medica *et al.,* 1996):

$$P_1 = P_0 (1 - \gamma (T_1 - T_0)) H/H_0 \quad (2)$$

Where:

P_0 = Power at standard condition (25°C and 1000 W/m^2)

H = Value of solar irradiance incident of the module (W/m^2)

H_0 is reference solar radiation =1000 W/m^2 (to the horizontal surface)

γ = Power correction coefficient

T_1 = Panel temperature

T_0 = Standard temperature (25°C)

From the above, it is evident that the output power of the PV panel is directly proportional to the sun's radiation, but also inversely proportional to the sun's heat. Solar radiation is comprised of about 9% ultra-violet, 41% of visible radiation (which increases the output current) and about 50% infrared, which constitutes the heat. Therefore, in order to maximize the electrical energy yield of a PV panel, one must minimize the effect of the heat component while maximizing the effect of the light component.

Currently there is no known technology that can filter the infrared before the solar radiation can strike the PV panel. However, the presence of other climatic factors at a location can impact on the temperature of the panel. These factors include wind speed, wind direction, humidity and due point. Consequently it may be necessary to rotate a panel slightly away from the position where it catches maximum radiation to one where catching a bit of a cool breeze (as well) results in more electrical energy yield.

The primary aim of this paper is to provide a comprehensive database of optimum tilt and azimuth angles to support PV installation engineers at any location in South Africa, regardless of how remote it may be.

3. Methodology

Initially an outline of a South African map was obtained and divided into grids. The intersection points of the grid lines were considered as the coordinate locations and used as locations for study. This is illustrated in Figure 2. These coordinates were used to generate climate data for each point on the map using *Meteonorm* climate simulation software. The simulated data contained the following output parameters namely, month, day of the month, hour, global radiation on a horizontal plane, diffuse radiation on a horizontal plane, air temperature, wind direction and wind speed. These are important in that they influence the overall performance of the PV module and need to be specified accurately for correct system design.

The climate data files were then inputted into PV Design Pro-S software and the annual energy yield for each intersection point was calculated. The design package allows the user to vary the azimuth and tilt angles of the panels used.

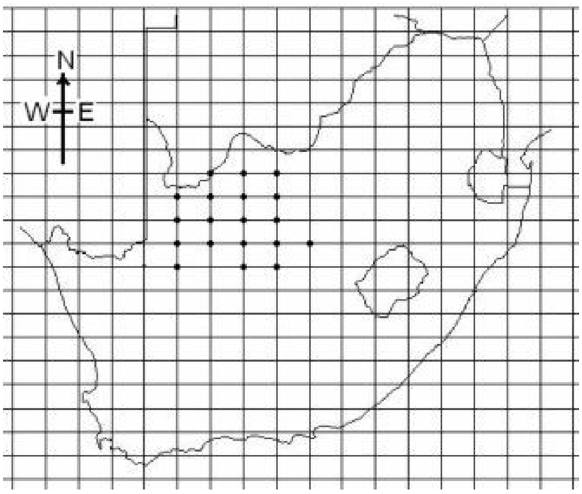

Figure 2: A South African map demarcated into grids of coordinate points

For a particular intersection point (coordinate location) the azimuth and tilt angle combination resulting in the highest annual energy yield was recorded. The rest of the parameters were kept constant. These included, the load profile, which was kept at an average of 18 466 Wh per day for weekly load and 18 000 Wh per day for the weekend load. Thus, the only parameters varied throughout the investigation were the climate (determined by the location), the tilt and azimuth angles.

4. Simulation results

4.1 Azimuth angle and tilt

Initially the assumption made was that the tilt angle could be set at latitude as suggested by Bekker (2007). Thus, to obtain the optimum azimuth angle, the tilt was kept constant at latitude and only the azimuth was varied until the maximum possible annual energy yield was obtained. This was repeated for all the points indicated in the map shown in Figure 2.

Once the optimum azimuth angles were obtained, the process was repeated to find the optimum tilt angles. Using the optimum azimuth angles obtained earlier, tilt angles were varied to obtain new values that yielded the maximum annual energy.

Tables 1 and 2 give the results of the optimum azimuth and tilt angles respectively, for all point locations investigated in this project. Table 1 shows a general trend of the azimuth angle increasing from west to east. This trend also holds in the case of the tilt angles as depicted in Table 2.

4.2 A guide to using the optimum yield angle tables

In practice a given location is unlikely to be at the coordinates indicated in the tables but somewhere in between. To address that problem, a method to obtain the required azimuth and tilt angles for any location is illustrated in this section.

In South Africa the average distance between any given adjacent longitude, ranges between approximately 90 km and 111 km. The distance between latitude degrees remains constant at roughly 111km. In addition, the results obtained from both Meteonorm and PV Design Pro-S are valid for a distance of approximately 40 km from the location where the results are obtained.

To obtain the coordinates of any location it is recommended that a GPS (global positioning system) be employed.

Linear Interpolation is a method of constructing new data points within the range of a discrete set of known points.

Table 1: Optimum Azimuth in degrees at coordinate points in South Africa

	Longitude																		
Coordinate	*16*	*17*	*18*	*19*	*20*	*21*	*22*	*23*	*24*	*25*	*26*	*27*	*28*	*29*	*30*	*31*	*32*	*33*	*34*
Latitude																			
23												45.2	51	53.1	53	49.5	56		
24											42.3	50.6	45.2	46	49.2	50	55		
25					33	32.8	32.1	37	41.8	41	42	44.4	49.9	47.1	49.1	53	53		
26					34.3	38.7	35	41	38.5	42.8	43	45.1	48	50	46.9	53	49.7		
27					33.6	35.9	38.6	40	41.1	44	45	47	49	53	51.8	52.3	57.6	55	
28	26.3	28	28.2	28.6	32	32	41	36.7	38	45	46	44	42.2	50	49	52.8	57	55.3	
29	28.9	29	27.4	29.7	37.8	37	43.1	41	40	42	41.4	43	47	48.4	44.5	51	53	56	
30		26.7	33.9	31.6	34.2	35.4	35.8	37.0	41.2	41.9	44	50.4	47.7	50.3	45.5	55.1	56.5		
31		29.7	30.7	36.4	31.5	36.7	34.3	36.1	38.3	42.2	43.9	43.6	49	47.3	50.1				
32			35.7	34	30,8	34	40.9	39.1	40.7	42.1	43.2	45.2	45.7	48	50.1				
33			40.1	37.7	38.8	41	47.1	44	47	48.6									
34			38.2	38.9	42.8	40.3	41.8	41	45.1	44.9	48.2								
35				38.2					46.3										

Table 2: Optimum tilt angles in degrees at coordinate points in South Africa

	Longitude																		
Coordinate	*16*	*17*	*18*	*19*	*20*	*21*	*22*	*23*	*24*	*25*	*26*	*27*	*28*	*29*	*30*	*31*	*32*	*33*	*34*
Latitude																			
23												258	256	257	265	262	265		
24											252	255	259	267	263	263	264		
25					229	244	242	241	246	252	255	252	256	259	254	261	261		
26					231	232	235	255	251	243	255	260	254	256	256	256	266		
27					236	240	246	239	249	250	249	255	259	250	254	253	259	259	
28	230	232	216	220	226	233	228	251	250	246	250	251	256	255	259	259	259	267	
29	238	221	218	225	235	233	237	242	247	241	253	255	248	254	257	261	259	269	
30		217	227	235	234	225	232	251	243	248	251	243	256	258	259	263	261		
31		226	233	229	215	225	221	231	242	242	244	247	257	257	263				
32			232	217	230	218	223	235	245	235	243	242	257	262	265				
33			234	225	221	240	239	242	248	256	249	257	258						
34			232	229	235	239	245	251	249	250	252								
35				227						250									

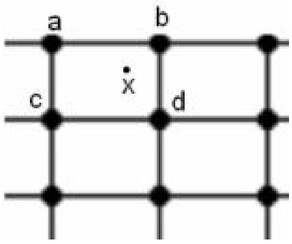

Figure 3: Coordinates a, b, c and d are given in the table but x is not

Figure 3 illustrates a location, x, that is not listed in the azimuth and tilt tables. The explanation below will illustrate how to obtain the required angles for x.

The first step is to interpolate the angles at two *new* points, r and s as illustrated in Figure 4.

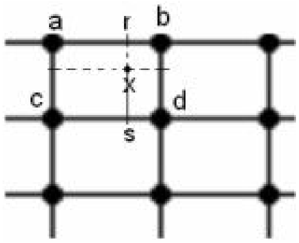

Figure 4: Illustration of the interpolation

Given the two known data points (a) and (b) in Figure 4, the required angle at r can be found as follows. Note that the closer r is to b the closer the values of their angles will be.

Let the angle at a be m and at b be n. (Assume that m is bigger than n).

Linear interpolation assumes that the values of the points from a to b decrease linearly from m to n. Then the total decrease between a and b is (m-n) units.

The decrease at r = [(m-n)ar/ ab]

Where,

ar is the distance between points a and r

ab is the distance between points a and b

Therefore the value at r = m – [(m-n)ar / ab]

Next (using the method above) one finds the value at s using the angles at c and d.

Finally, using the values obtained at r and s, one interpolates the value at x.

4.3 Verification of the Interpolation Method

Table 4 compares annual energy yield obtained from the interpolated yield angles with that of the simulated yield angles. Eight sample locations were considered. Also included, is the error between the two, calculated and simulated energy yield results.

From Table 3 it is clear that the percentage error in annual energy yield between the results obtained from the interpolated yield angles and simulated yield angles is small, thus negligible. Hence the interpolation method is accurate.

5. Concluding remarks

The cost of PV technology remains high in South Africa and it is important to optimise system design and performance to minimise installation costs. Due to a number of climatic and location related parameters, traditional installations that are fixed at tilt angles dependent on latitude alone do not attain optimum annual energy yields.

In this paper the tables of optimum azimuth and tilt angles for locations in South Africa have been successfully produced. GPS tools are now readily available to consumers and can be used to determine the coordinates of any given location. In addition, the linear interpolation method for calculating the optimum yield angles at any location has been demonstrated and validated through simulation.

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Table 3: Comparison between calculated and simulated annual energy yield for sample points not on the map

Location	*Interpolated annual energy yield*	*Simulated annual energy yield*	*Error (%)*
X1 (27°S – 24.5°E)	56.883	56.909	0.046
X2 (27°S – 25.5°E)	55.701	55.608	- 0.166
X3 (27°S – 26.5°E)	52.892	55.948	0.106
X4 (27°S – 27.5°E)	53.835	53.870	0.065
Y1 (27.5°S – 24°E)	56.574	56.565	- 0.016
Y2 (28.5°S – 24°E)	58.066	58.145	0.136
Y3 (29.5°S – 24°E)	56.490	56.459	- 0.055
Y4 (30.5°S – 24°E)	55.907	55.968	0.109

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