

Maximum energy azimuth and tilt angles for PV installations in South Africa

by Tebogo Matshoge, University of Cape Town and Adoniya Ben Sebitosi, University of Stellenbosch

Photovoltaic (PV) technology is fast emerging as a viable alternative to fossil fuel based power generation. Current research efforts to improve efficiency are mainly focused on component physics and manufacturing technologies and little attention seems to be paid to improved system design at field level. 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.

South Africa is currently facing a range of energy related problems that include energy reliability, environmental sustainability and electricity tariff hikes [4,5,6]. 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 [2]. 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 totaling 5 MW. Despite this great potential, solar PV installations are still very expensive for ordinary users, more especially those in rural South Africa, and cost is one of the major limiting factors to the full utilisation of PV technologies.

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 use fixed mountings. Fig. 1 illustrates the reduction

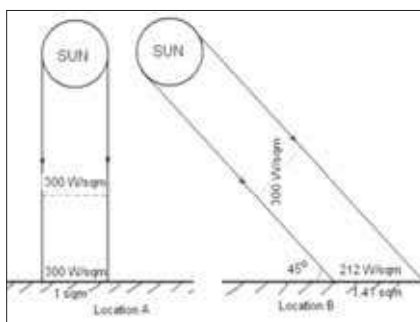


Fig. 1: An illustration of the reduction of radiation intensity per m^2 due to sun angle.

in solar intensity with change in angle of irradiation.

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 PV panel consists of several solar cells. 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 Eqn. 1.

$$I = I_0 \left(e^{\frac{qV}{kT}} - 1 \right)$$

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 [3].

$$P_i = P_o (1 - \gamma (T_i - T_o)) H/H_o \quad (2)$$

where:

P_o = Power at standard condition (25°C and 1000 W/m²)

H = Value of solar irradiance incident of the module (W/m²)

H_o is reference solar radiation = 1000 W/m² (to the horizontal surface)

γ = Power correction coefficient

T_i = Panel temperature

T_o = 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 maximise the electrical energy yield of a PV panel, one must minimise the effect of the heat component while maximising the effect of the light component.

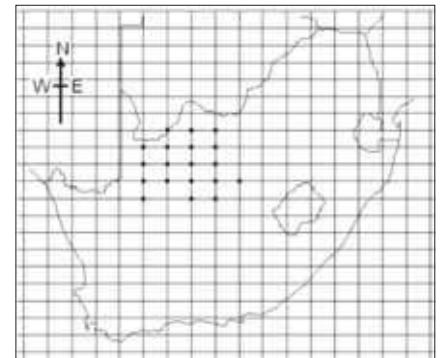


Fig. 2: A South African map demarcated into grids of coordinate points.

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 dew 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.

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 Fig. 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.

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

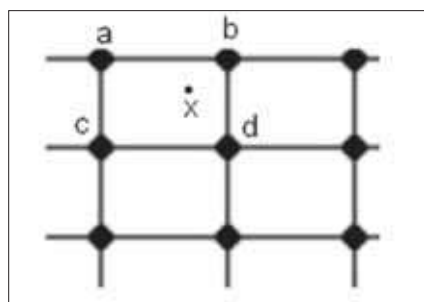


Fig. 3: Coordinates a, b, c and d are given in the table but x is not.

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.

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.

Simulation results

Azimuth angle and tilt

Initially the assumption made was that the tilt angle could be set at latitude as suggested by Bekker [1]. 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 Fig. 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.

A guide to using the optimum yield angle tables

In South Africa the average distance between any given adjacent longitude, ranges between approximately 90 and 111 km. The distance between latitude degrees remains constant at roughly 111 km. 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

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									

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

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

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

constructing new data points within the range of a discrete set of known points. Fig. 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 Fig. 4.

Given the two known data points (a) and (b) in Fig. 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 .

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.

Concluding remarks

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

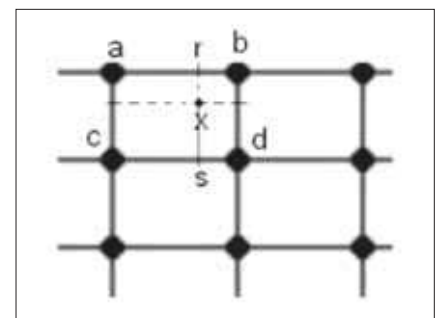


Fig. 4: Illustration of the interpolation.

at any location has been demonstrated and validated through simulation.

Acknowledgement

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Contact Adoniya Ben Sebitosi,
University of Stellenbosch,
Tel 073 498-7221, sebitosi@sun.ac.za ❖