Comparing and Optimizing of Solar Insolation on Yearly, Monthly and Seasonally Basis for Solar Devices Performance in Nepal

Rijan Karkee, Sumit Khadka, Gaurav Luitel, Mausham Devkota, Bibek Khadka, Shushilata Sapkota, Puja Bhetwal

Abstract—Solar Photovoltaic panels and solar water heating systems are the most used form of harnessing solar energy (utilizing both diffuse and direct radiation) and evidently, the power harnessed by the system is dependent on location, time of the day, the amount of sunshine hours, cloud cover etc. The orientation of the solar energy harnessing devices is another important factor and in fact, the factor that can be easily controlled for maximum power harnessing. This paper presents the calculation of the optimal tilt angle of solar energy devices according to different month, seasons (summer and winter) as well as for a year based on average data of insolation previously recorded for 5 different places of Nepal (latitude 26.45°N to 29.27°N). Furthermore, the solar insolation for yearly fixed optimal tilt angle versus seasonal tilt angles has also been discussed and is compared.

Index Terms—optimal tilt angle, solar devices, solar radiations

I. INTRODUCTION

The ever increasing trend of the global and regional energy consumption coupled with the need for reduction of pollutants has led to increase in use of renewable energy systems, primarily Solar Photovoltaic (PV) systems [1]; mostly because of its usability and technological friendliness. On one hand, the efficiency of laboratory solar cells have been significantly improved and it is expected that these improvements be available in commercial cells as well, and on the other hand, the cost of Solar Photovoltaic modules have also been decreased [2]. All these developments are sure to increase the use of solar panels as well as promoting clean and green energy.

Harnessing as much energy as possible is the primary objective of any energy systems and in the case of photovoltaic systems (or any other solar energy systems), this can be achieved by intercepting maximum sunlight by positioning PV panels normal to the path of sun rays; but the trajectory of sun is not similar throughout the year. Figure (1 and 2) shows how sun’s trajectory varies at latitude 27.7°N, from maximum to minimum. The figures have been extracted from the Motion of Sun Simulator, Astronomy Education at University of Nebraska-Lincoln, USA [14]. The red curve in figure below shows the trajectory from minimum to maximum representing month January and June respectively. The rest of month’s trajectory lies in between those two curves.

Figure 1: Trajectory of sun at latitude 27.7° N in January

Figure 2: Trajectory of sun at latitude 27.7° N in June

The best, at least ideal, solution is to use tracking systems [3]. A tracker is a mechanical device (usually coupled with electronics) that follows the direction of the sun across the sky. However, trackers are expensive, and bulky, thus, are not always feasible [4], at least not in regular domestic purposes. Thus, in many applications, installations with fixed
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Table I: Different suggestions made by different authors

<table>
<thead>
<tr>
<th>References</th>
<th>Recommended Tilt Angle (degrees)</th>
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<tbody>
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<td>Duffie and Beckman [6]</td>
<td>(Φ+15)±15</td>
<td>Φ is latitude angle. The – and + sign is used for summer and winter season respectively.</td>
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<tr>
<td>Heywood [7]</td>
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<td>Lunde [8]</td>
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<td>Chinnery [9]</td>
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<td>Hotte [10]</td>
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<td>Yellot [12]</td>
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<tr>
<td>Elminir et al. [13]</td>
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</tr>
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Table II: Average of horizontal global insolation data from July 1983 to June 2005

<table>
<thead>
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<th>Month</th>
<th>Kathmandu</th>
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<th>Biratnagar</th>
<th>Mahendranagar</th>
<th>Jumla</th>
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<td>6.2355</td>
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<td>6.027076</td>
<td>5.411985</td>
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<tr>
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<td>5.32566</td>
<td>4.403563</td>
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</tr>
<tr>
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<tr>
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Table III: Average of diffuse insolation data from July 1983 to June 2005

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<td>0.818768</td>
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Figure 3: Average of 22 years Horizontal global Insolation on Kathmandu

Figure 4: Average of diffuse insolation on Kathmandu
orientation or installations where the tilt angle can be adjusted manually are used. With the optimum tilt angle and the optimum azimuth angle, a power production of about 10-20% greater than the power production using usual installation can be achieved [5].

For northern hemisphere (in case of Nepal), the optimum azimuth angle will be facing true south, i.e. \( \gamma = 0^\circ \). The optimal tilt angle of a place depends on local latitude. Usually in northern hemisphere, solar photovoltaic are tilted at an angle approximately equal to the value of the latitude angle. However, this method only considers the movement of the sun throughout the year and does not incorporate other factors such as cloud cover, temperature etc. Attempts have been made by various authors to identify the optimum tilt angle for solar collectors and PV systems which are summarized in Table I. Table I shows the recommended tilt angle for general location, but for even more accurate calculations the location specific calculations must be done because they incorporate various factors such as cloud cover, weather conditions etc. We have used the global and diffuse radiation data of various locations of Nepal as per recorded by the Atmospheric Science Data Center, NASA Surface Meteorology and Solar Energy [15]. Global, diffuse, and clear sky insolation data from July 1983 to June 2005 has been retrieved from The Atmospheric Science Data Center. The recorded data have been averaged in different required headings. Based on previously recorded data, the global and diffuse data can also be predicted theoretically [16-19]. Krishna et al [17] has formulated the equation to calculate the global radiation on four different parts of Nepal using statistical method. The averaged insolation data of 22 years (July 1983 to June 2005) have been plotted to understand the trend in Figure 3 & 4. Table II and Table III present the average value of horizontal global insolation and diffuse insolation from July 1983 to June 2005 over different parts of Nepal.

II. SURVEY FOR ORIENTATION OF SOLAR PANELS

A sample survey was conducted to determine orientation of PV module and solar collectors followed by direct questionnaires with resident of around 500 homes in Kathmandu and Bhaktapur district. The tilt angle of panels was determined by android application called as “Clinometer”. The accuracy of software was tested before it was used for measuring tilt angle of panels and the accuracy of the application was found to be of ±0.7° order. Similarly, the surface azimuth angle of panels was determined by using modified magnetic compass. In our sample survey we found that 97% of installed panels were not even placed facing true south and on average the azimuth angle was found to be offset by 10°. Furthermore, we also inquired public if they were interested in seasonal optimized tilt system (orienting panel twice a year) for better performance and 99.99% voted affirmatively for manual tilt angle adjustment. In Nepal almost all houses have flat roofs and thus installed solar panels have easy human access for maintenance and operation. So, it won’t be difficult for people to change the panel’s tilt angle twice in a year. Furthermore, on average 100W panel was used for domestic purpose. So, it should not be difficult to change the panel tilt angle because of its weight. Similarly, the mechanism to adjust the tilt angle twice a year, once for the winter and once for the summer will be very simple and inexpensive.

III. RADIATION ON TILTED SURFACE

Liu and Jordan [20] first suggested the way to calculate the radiation falling in tilted surface. Later, based on Liu and Jordan suggestion, Klein [21] developed a mathematical relationship to calculate global radiation on any tilted surface. Now, many authors use that relation to estimate the optimal tilt angle on various locations on earth [22-24]. We shall too use that relation for determining different optimal tilt angle over different part of Nepal.

The monthly average daily total radiation on a tilted surface \( H_T \) is usually estimated by the summation of the direct beam \( H_B \), the diffuse \( H_D \) and the reflected components \( H_R \) of the radiation on a tilted surface. Thus, for a surface tilted at a slope angle from the horizontal, total incident radiation is given by

\[
H_T = H_B + H_D + H_R
\]

The direct radiation incident on tilted surface is given by

\[
H_B = (H - H_d)R_b
\]

Here \( 'H' \) and \( 'H_d' \) are the monthly averaged global radiation and diffuse radiation respectively on the horizontal surface and \( R_b \) is the ratio of the average daily beam radiation on a tilted surface to that on a horizontal surface and for the surface in the northern hemisphere facing towards the equator (facing true south), i.e. for surfaces with \( (\gamma=0) \) the equation for \( R_b \) is given as [21]

\[
R_b = \frac{\cos(\varphi - \beta) \cos \delta \cos \omega_s + \frac{\pi}{180} \omega_s \sin(\varphi - \beta) \sin \delta}{\cos \omega_s \cos \delta \sin \omega_s + \frac{\pi}{180} \omega_s \sin \omega_s \sin \delta}
\]

Here, \( \omega_s \) is the sunset hour angle for the tilted surface and is determined by

\[
\omega_s = \text{min} \left[ \cos^{-1}(-\tan \alpha), \cos^{-1}(-\tan(\varphi - \beta) \tan \delta) \right]
\]

In equation (4) ‘min’ implies that minimum value of the terms separated by comma. Similarly, for the southern hemisphere, the equation of \( R_b \) is slight different, i.e.

\[
R_b = \frac{\cos(\varphi + \beta) \cos \delta \cos \omega_s + \frac{\pi}{180} \omega_s \sin(\varphi + \beta) \sin \delta}{\cos \omega_s \cos \delta \sin \omega_s + \frac{\pi}{180} \omega_s \sin \omega_s \sin \delta}
\]

With modified \( \omega_s \) as

\[
\omega_s = \text{min} \left[ \cos^{-1}(-\tan \alpha), \cos^{-1}(-\tan(\varphi + \beta) \tan \delta) \right]
\]
Now the second part of equation (1) can be obtained by
\[ H_{T} = H_{0}R_{d} \]  
(7)

Here, \( R_{d} \) is the ratio of the average daily diffuse radiation on a tilted surface to that on a horizontal surface. There has been introduced various model (isotropic and anisotropic) for the calculation of \( R_{d} \)[25]. But we follow the most commonly used model (Liu and Jordan [20]) i.e.
\[ R_{d} = \frac{1 + \cos \beta}{2} \]  
(8)

Similarly, third term in equation (1) \( H_{b} \) is given by
\[ H_{b} = H\rho R_{r} \]  
(9)

Here \( R_{r} \) is the tilt factor for reflected radiation which is given by
\[ R_{r} = \frac{1 - \cos \beta}{2} \]  
(10)

Here, \( \rho \) is the reflectivity of the surrounding in which the collector is located. Normally, a value of about 0.2 is taken for the reflectivity of grass or concrete. But, in general, the contribution of the reflected radiation is quite small.

Thus combining all equations from equation (2) to equation (10), the equation (1) can be re-written as
\[ \frac{H_{T}}{H} = \left(1 - \frac{H_{d}}{H}\right)R_{b} + \frac{H_{d}}{H}R_{d} + \rho R_{r} \]  
(11)

The values of \( H \) and \( H_{d} \) is found by averaging out the 22 years data. It is then solved in MATLAB by programming the equation (11) to calculate the radiation on tilted surface (see appendix).

IV. RESULTS

After computation work, several results were obtained including yearly optimal angle, monthly based optimal angle, seasonal (summer and winter) based optimal angle with maximum value of insolation. The table below shows the different monthly based optimal angle for five different places in Nepal. The places are so chosen in order to account the latitude variation since it is estimated that insolation remains uniform for same latitude. The places are Biratnagar (26.45°N), Mahendranagar (28.98°N), Kathmandu (27.1°N), Pokhara (28.23°N) and Jumla (29.27°N). So, we actually varied the calculation from lowest of 26.45°N latitude to highest of 29.27°N latitude. We also assume that almost all other places lie within these mentioned latitudes.

Table IV and Table V presents the values of monthly optimal tilt angle at which maximum insolation can be intercepted. Also, in these tables we have mentioned the insolation values calculated over a given month (KWh/m²/day). The values were obtained by programming in MATLAB. Table IV and Table V are important for knowing monthly based optimal tilt angles. A Figure 5 shows the trend of the monthly based optimal tilt angle that has been presented in Tables IV and V. There is almost a similar trend for all places. The cause of similar trend is that the distance since Nepal is a small country and the locations that are being chosen are not at great distant apart.

It is not always feasible to manually change the tilt angle of panel every month. It is required to determine the yearly based optimal tilt angle for which output is best. Table I predicts theoretical possible optimal tilt angle based on latitude but the better way to figure out is by calculating from previously recorded values of global and diffuse insolation as it best represents the climatic and other local conditions. The process to find tilt angle is best by programming as manual calculation is tedious and lengthy. In MATLAB programming, we not only find the optimal angle over a year but also we have included the winter and summer optimal tilt angle. Here, we have treated January, February, March, October, November and December as winter season while April, May, June, July, August, and September as summer season. We divided this accordingly from trend in Figure 5 and Table IV and V. In above mentioned figures and tables we can see that those defined months have almost closer optimal angle and insolation values. The Table VI and Table VII are an important result of this paper. In Table VI, we have mentioned the yearly optimal tilt angle and the corresponding insolation values in a unit of KWh/m²/day. Similarly, we have compared the total insolation value for a year that would be obtained by orienting in winter and summer based optimal tilt angle in Table VII. In this case, the panels must be tilted into two different angles over a year i.e. one in winter season while other in summer season. The respective optimal angle for winter and summer seasons are presented in Table VII. The column 6th of Table VII is the insolation value combining winter and summer optimal tilt angle over a year. The column 4th of Table VI is the insolation value that would be obtained if the panels were tilted twelve times over a year according to monthly based optimum tilt angle as shown in Table IV and V. These values on column 4th of Table VI are the summation of monthly optimal insolation (KWh/m²/day) over a year.

Similarly, Figure 6 displays the difference in values for several orientation techniques. From Figure 6, one can see clearly that the difference in fixed yearly based optimum angle with that of winter-summer combination or monthly based tilt angle. It is not really practical to change the tilt angle for panels every month. Based on sample survey, it will be feasible, at least in Nepal, to change the panel tilt angle twice a year to get a better performance.

The Table VIII shows quantitatively how better the performance would increase in reference to fixed yearly optimal tilt orientation. The values differ from place to place. So, for Nepal, the collecting of solar insolation can boost up to 6% in average all over Nepal if seasonal based tilt angle is practiced. Similarly, there are only a few percentages better in practicing monthly based tilt orientation. The manual operation is tedious and it is not recommended to practice because of not much higher insolation collection.
Table IV: Optimal tilt angle and total insolation (KWh/m²/day) for a given month for different places

<table>
<thead>
<tr>
<th>Month</th>
<th>Kathmandu</th>
<th>Pokhara</th>
<th>Biratnagar</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Optimum Angle</td>
<td>Insolation over month</td>
<td>Optimum Angle</td>
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<td>48</td>
<td>204.193</td>
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<td>Mar</td>
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<td>221.593</td>
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</tr>
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<td>May</td>
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<td>Jun</td>
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<td>Aug</td>
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<td>Nov</td>
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<td>Dec</td>
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<td>60</td>
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Table V: Optimal tilt angle and total insolation (KWh/m²/day) for a given month for different places

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<tr>
<th>Mahendranagar</th>
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<td>Feb</td>
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<td>Mar</td>
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<td>44</td>
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<tr>
<td>Nov</td>
<td>56</td>
</tr>
<tr>
<td>Dec</td>
<td>60</td>
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Table VI: Yearly and monthly insolation (KWh/m²/day) with yearly based optimum tilt angle

<table>
<thead>
<tr>
<th>Place</th>
<th>Yearly optimal angle</th>
<th>Yearly Optimized Insolation</th>
<th>Monthly Optimized Insolation for a year</th>
</tr>
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<td>2346.281</td>
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<td>32</td>
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<td>2306.773</td>
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<td>2249.239</td>
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Table VII: Seasonal insolation (KWh/m²/day) with optimum tilts angles

<table>
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<tr>
<th>Place</th>
<th>Winter optimal angle</th>
<th>Winter Optimized Insolation</th>
<th>Summer optimal angle</th>
<th>Summer Optimized Insolation</th>
<th>Winter + Summer Optimized Insolation</th>
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<td>1299.6</td>
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<td>5</td>
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Table VIII: Comparison in % increase in performance against fixed yearly optimal tilt angle

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<thead>
<tr>
<th>Place</th>
<th>% Increase in Winter-Summer Tilt orientation (two times a year)</th>
<th>% Increase in monthly based optimal tilt orientation (twelve times a year)</th>
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<tr>
<td>Kathmandu</td>
<td>6.52</td>
<td>7.84</td>
</tr>
<tr>
<td>Pokhara</td>
<td>6.86</td>
<td>8.26</td>
</tr>
<tr>
<td>Biratnagar</td>
<td>6.31</td>
<td>7.54</td>
</tr>
<tr>
<td>Mahendranagar</td>
<td>6.46</td>
<td>7.81</td>
</tr>
<tr>
<td>Jumla</td>
<td>7.13</td>
<td>8.61</td>
</tr>
</tbody>
</table>

Figure 5: Monthly optimal angles for different places in Nepal
VI. CONCLUSION

In this paper, we first determined the optimal tilt angle for collecting maximum solar insolation in different parts of Nepal which were not known before. Apart from this, we took a sample survey in different houses in Kathmandu and Bhaktapur. We interviewed the interest of people based on increase in performance of panels for seasonal based tilt orientation. Furthermore, in Nepal, the panels are generally placed in a flat roof where there won’t be difficulties in changing the panel tilt angle once in a six month. Thus we highly recommend solar distributing companies in Nepal with a little improvement in base for holding solar panels just to change panels into two different angles for winter and summer seasons so as to enhance the interception of sunlight up to 6% in average. Furthermore, our paper also concludes that seasonal based tilting method (winter and summer) is way better of collecting solar insolation than fixed yearly optimal tilt orientation. Furthermore, it is seen that there won’t be significant increase in insolration collection if tilting of panels is done on monthly optimal angles (12 times a year). So, seasonal variation (twice a year) is best practice for manual operation to intercept radiation thus increasing performance of devices in Nepal.

VI. APPENDIX

The following is the sample program used for calculating optimal tilt angle and values.

```matlab
function pokhara
DIF=[0.453152493 0.664472141 0.806121212 0.948592375 1.071658689 1.2610322581 0.664472141 0.806121212 0.948592375 1.071658689 1.2610322581 0.664472141];
GLOBAL=[repmat(DIR(1),1,31) repmat(DIR(2),1,28) repmat(DIR(3),1,31) repmat(DIR(4),1,30) repmat(DIR(5),1,31) repmat(DIR(6),1,30) repmat(DIR(7),1,31) repmat(DIR(8),1,31) repmat(DIR(9),1,30) repmat(DIR(10),1,31)];
DIFFUSE=[repmat(DIF(1),1,31) repmat(DIF(2),1,28) repmat(DIF(3),1,31) repmat(DIF(4),1,30) repmat(DIF(5),1,31) repmat(DIF(6),1,30) repmat(DIF(7),1,31) repmat(DIF(8),1,31) repmat(DIF(9),1,30) repmat(DIF(10),1,31)];
% changes latitude
phi=28.23;
% changes month values
Jan=31;
Feb1=32;
Feb2=59;
Mar1=60;
Mar2=90;
Apr1=91;
Apr2=120;
May1=121;
May2=151;
Jun1=152;
Jun2=181;
Jul1=182;
Jul2=212;
Aug1=213;
Aug2=243;
Sep1=244;
Sep2=273;
Oct1=274;
Oct2=304;
Nov1=305;
Nov2=334;
Dec1=335;
Dec2=365;
% k is for tilt angle up to 90 degrees
for k=0:90
% j is for fixing days to calculate optimum angle
for j=1:365
ca=GLOBAL(j)^*(1-DIFFUSE(j)/GLOBAL(j));
delta=23.5*sin(360*((284+j)/365));
r1=(-tan(phi)*tan(delta));
r2=(-tan(phi-k)*tan(delta));
if (r2<=1 & & r2>=-1)
w=min((acosd(r1) acosd(r2)));
else
w=acosd(r1);
end
ws=acosd(-tan(phi)*tan(delta));
%Mention the following while calculating for winter season and run j loop from 1 to 365
% if (j>Mar2 & & j<Oct1)
% H(j)=0;
% else
H(j)=(CA *((cos((cos(phi-k)*cos(delta)*sin(w))+(pi/180)*w*sin(phi-k)*sin(delta)))/(cos(phi)*cos(delta)*sin(w)+pi/180)*w*sin(phi)*sin(delta)))+DIFFUSE(j)^*(1+cos((cos(phi-k))/2)+0.2*GLOBAL(j)^*(1-cos((cos(phi-k))/2));
% end
ans(k+1)=sum(H);
end
Maxvalue=max(ans)
Optangle=(find(ans==Maxvalue))-1
```

Figure 6: Comparison of insolation based on yearly, monthly and bi-annually
VII. ACKNOWLEDGEMENT

We are very thankful to our parents who encouraged us to continue our work despite of having no any fund. All financial support has been collected individually by authors with no outside fund except from parents. We are also thankful to Mr. Ishan Bhattarai who assisted us in surveying and preparing questionnaire. We would like to appreciate Atmospheric Science Data Center, NASA Surface Meteorology and Solar Energy for providing data for free.

VIII. NOMENCLATURE

\[ H = \text{daily global radiation incident on a horizontal surface, KWh/m}^2/\text{day} \]
\[ H_d = \text{daily diffuse radiation incident on a horizontal surface, KWh/m}^2/\text{day} \]
\[ H_s = \text{daily diffuse radiation incident on an inclined surface, KWh/m}^2/\text{day} \]
\[ H_T = \text{daily radiation on a tilted surface, KWh/m}^2/\text{day} \]
\[ H_R = \text{daily ground-reflected radiation incident on an inclined surface, KWh/m}^2/\text{day} \]
\[ H_B = \text{daily direct radiation incident on tilted surface, KWh/m}^2/\text{day} \]
\[ \beta = \text{surface slope from the horizontal, degrees} \]
\[ \delta = \text{declination, degrees} \]
\[ \omega_s = \text{sunrise hour angle, degrees} \]
\[ \omega_e = \text{sunrise hour angle for a tilted surface, degrees} \]
\[ \varphi = \text{latitude, degrees} \]
\[ \rho = \text{ground albedo} \]
\[ \gamma = \text{surface azimuth angle, degrees} \]

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