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

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***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^{0}N to 29.27^{0}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 27.7^0 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.

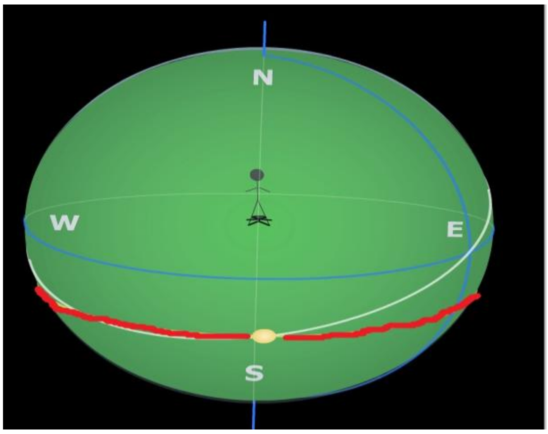

Figure 1: Trajectory of sun at latitude 27.7^0 N in January

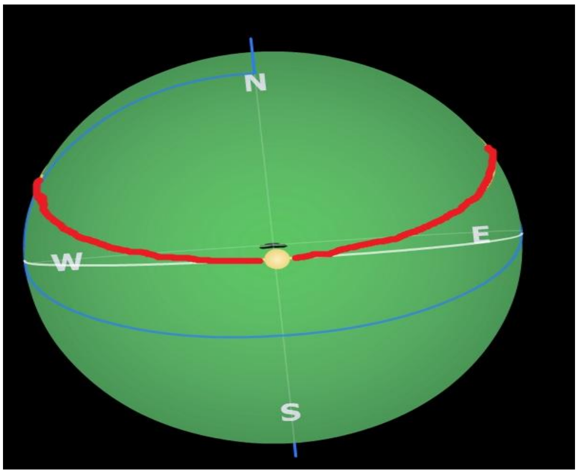

Figure 2: Trajectory of sun at latitude 27.7^0 N in June

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

References	Recommended Tilt Angle (degrees)	Remarks
Duffie and Beckman [6]	(Φ+15)±15	Φ is latitude angle. The – and + sign is used for summer and winter season respectively.
Heywood [7]	Φ-10	
Lunde [8]	Φ±15	
Chinnery [9]	Φ+10	
Hottel [10]	Φ+20	
Kern and Harris [11]	Φ+10	
Yellot [12]	Φ+20	
Elminir et al. [13]	(Φ+15)±15	

Table II: Average of horizontal global insolation data from July 1983 to June 2005

Average of horizontal global insolation (KWh/m^2/day) from 1983-2005 [15]					
Month	Kathmandu	Pokhara	Biratnagar	Mahendranagar	Jumla
Jan	4.26085	3.984868	4.198284	3.769003	3.708255
Feb	5.153071	4.570241	5.194486	4.89799	4.363714
Mar	6.18063	5.539047	6.201188	6.053944	5.269047
Apr	6.756424	6.2355	6.664182	7.100227	6.180409
May	6.67717	6.483475	6.523636	7.372478	6.842243
Jun	5.753652	6.027076	5.411985	6.4125	6.643955
Jul	4.786026	5.32566	4.403563	5.083592	6.003299
Aug	4.799839	5.010323	4.528109	4.618328	5.442463
Sep	4.564818	4.814682	4.342803	4.779742	5.210924
Oct	5.128504	5.073416	4.94412	5.287478	5.353226
Nov	4.715	4.476485	4.741167	4.582015	4.59447
Dec	4.14717	3.97849	4.138988	3.785264	3.897419

Table III: Average of diffuse insolation data from July 1983 to June 2005

Average of clear sky diffuse insolation (KWh/m^2/day) from 1983-2005 [15]					
Month	Kathmandu	Pokhara	Biratnagar	Mahendranagar	Jumla
Jan	0.584399	0.453152	0.68544	0.66066	0.37371
Feb	0.669871	0.530225	0.793489	0.781158	0.415659
Mar	0.812258	0.664472	0.943739	0.884795	0.521906
Apr	0.92003	0.806121	1.050455	1.020985	0.61147
May	1.045762	0.948592	1.176935	1.116276	0.755865
Jun	1.16847	1.025045	1.266848	1.224576	0.914
Jul	1.243915	1.10632	1.321085	1.295674	1.03195
Aug	1.19088	1.071657	1.276393	1.279413	0.987463
Sep	1.059939	0.932682	1.156727	1.117182	0.807773
Oct	0.818768	0.673504	0.931921	0.883006	0.548959
Nov	0.639955	0.512727	0.731424	0.705758	0.394424
Dec	0.565704	0.435103	0.662918	0.627757	0.357317

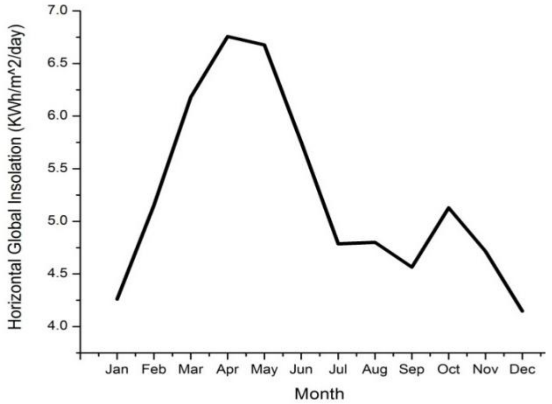

Figure 3: Average of 22 years Horizontal global Insolation on Kathmandu

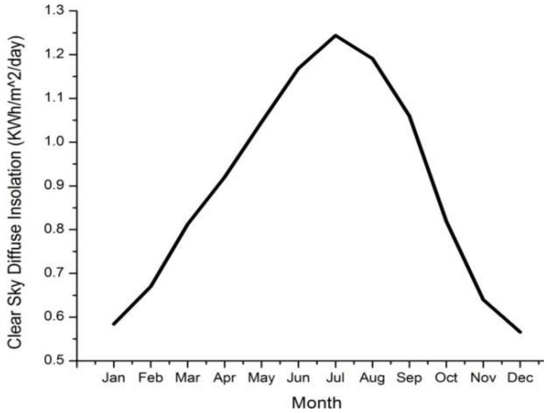

Figure 4: Average of diffuse insolation on Kathmandu

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. $\gamma = 0^o$. 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^{0}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 by10^o.

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_S) 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

$$H_T = H_B + H_S + H_R \quad (1)$$

The direct radiation incident on tilted surface is given by

$$H_B = (H - H_d)R_b \quad (2)$$

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 (γ=0) the equation for R_b is given as [21]

$$R_b = \frac{\cos(\varphi-\beta)\, cos\delta sin\omega_s' + \frac{\pi}{180}\omega_s' \sin(\varphi-\beta) sin\delta}{cos\varphi cos\delta sin\omega_s + \frac{\pi}{180}\omega_s sin\varphi sin\delta} \quad (3)$$

Here, $\omega_s'$is the sunset hour angle for the tilted surface and is determined by

$$\omega_s' = \min\left[\cos^{-1}(-tan\varphi tan\delta),\ \cos^{-1}(-\tan(\varphi-\beta)\, tan\delta)\right] \quad (4)$$

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.

$$R_b = \frac{\cos(\varphi+\beta)\, cos\delta sin\omega_s' + \frac{\pi}{180}\omega_s' \sin(\varphi+\beta) sin\delta}{cos\varphi cos\delta sin\omega_s + \frac{\pi}{180}\omega_s sin\varphi sin\delta} \quad (5)$$

With modified ω_s' as

$$\omega_s' = \min\left[\cos^{-1}(-tan\varphi tan\delta),\ \cos^{-1}(-\tan(\varphi+\beta)\, tan\delta)\right] \quad (6)$$

Now the second part of equation (1) can be obtained by

$$H_S = H_d R_d \qquad (7)$$

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.

$$R_d = \frac{1 + cos\beta}{2} \qquad (8)$$

Similarly, third term in equation (1) H_R is given by

$$H_R = H\rho R_r \qquad (9)$$

Here R_r is the tilt factor for reflected radiation which is given by

$$R_r = \frac{1 - cos\beta}{2} \qquad (10)$$

Here, ρ 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

$$\frac{H_T}{H} = \left(1 - \frac{H_d}{H}\right) R_b + \frac{H_d}{H} R_d + \rho R_r \qquad (11)$$

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 (26.45^0N), Mahendranagar(28.98^0N), Kathmandu(27.71^0N), Pokhara (28.23^0N) and Jumla (29.27^0N). So, we actually varied the calculation from lowest of 26.45^0N latitude to highest of 29.27^0N 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/m^2/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 5and 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/m^2/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/m^2/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 ($KWh/m^2/day$) for a given month for different places

	Kathmandu		Pokhara		Biratnagar	
Month	Optimum Angle	Insolation over month	Optimum Angle	Insolation over month	Optimum Angle	Insolation over month
Jan	57	222.918	58	213.79	55	210.766
Feb	48	204.193	49	183.808	47	199.785
Mar	33	221.593	33	200.133	31	218.750
Apr	13	207.066	14	191.5	12	203.275
May	0	206.992	0	200.987	0	202.232
Jun	0	172.609	0	180.812	0	162.359
Jul	0	148.366	0	165.095	0	136.510
Aug	6	149.382	7	156.091	5	140.694
Sep	24	147.373	25	156.803	23	138.560
Oct	43	207.114	44	208.504	41	194.305
Nov	55	228.230	56	221.604	53	221.672
Dec	59	230.440	60	227.640	58	220.325

Table V: Optimal tilt angle and total insolation ($KWh/m^2/day$) for a given month for different places

Mahendranagar			Jumla	
Month	Optimum Angle	Value	Optimum Angle	Maximum Value
Jan	57	197.9167	59	205.230
Feb	49	195.515	50	180.381
Mar	34	219.0805	35	193.407
Apr	14	218.5231	15	190.819
May	0	228.5468	0	212.109
Jun	0	192.375	0	199.318
Jul	0	157.5914	0	186.102
Aug	7	143.9439	8	169.912
Sep	26	155.5457	27	171.976
Oct	44	216.747	46	226.062
Nov	56	225.1785	57	236.332
Dec	60	212.4619	61	231.280

Table VI: Yearly and monthly insolation ($KWh/m^2/day$) with yearly based optimum tilt angle

Place	Yearly optimal angle	Yearly Optimized Insolation	Monthly Optimized Insolation for a year
Kathmandu	32	2175.7	2346.281
Pokhara	32	2130.8	2306.773
Biratnagar	30	2091.6	2249.239
Mahendranagar	31	2192.2	2363.425
Jumla	32	2212.4	2402.933

TableVII: Seasonal insolation ($KWh/m^2/day$) with optimum tilts angles

Place	Winter optimal angle	Winter Optimized Insolation	Summer optimal angle	Summer Optimized Insolation	Winter + Summer Optimized Insolation
Kathmandu	50	1299.6	4	1017.9	2317.5
Pokhara	51	1241.4	4	1035.6	2277
Biratnagar	48	1251.2	2	972.2912	2223.49
Mahendranagar	50	1253.2	5	1080.6	2333.8
Jumla	52	1258.9	5	1111.2	2370.1

Table VIII: Comparison in % increase in performance against fixed yearly optimal tilt angle

Place	% Increase in Winter-Summer Tilt orientation (two times a year)	% Increase in monthly based optimal tilt orientation (twelve times a year)
Kathmandu	6.52	7.84
Pokhara	6.86	8.26
Biratnagar	6.31	7.54
Mahendranagar	6.46	7.81
Jumla	7.13	8.61

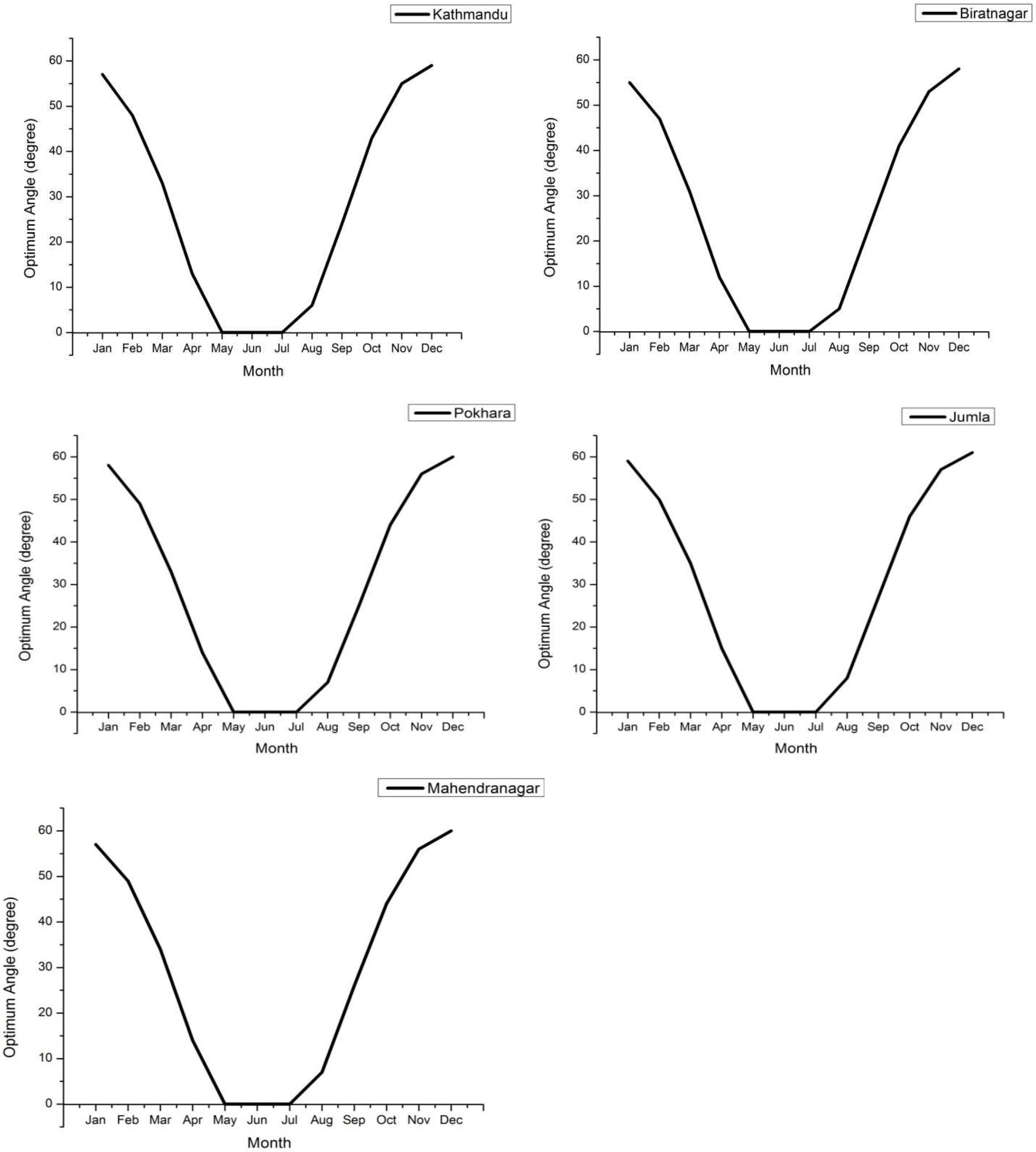

Figure 5: Monthly optimal angles for different places in Nepal

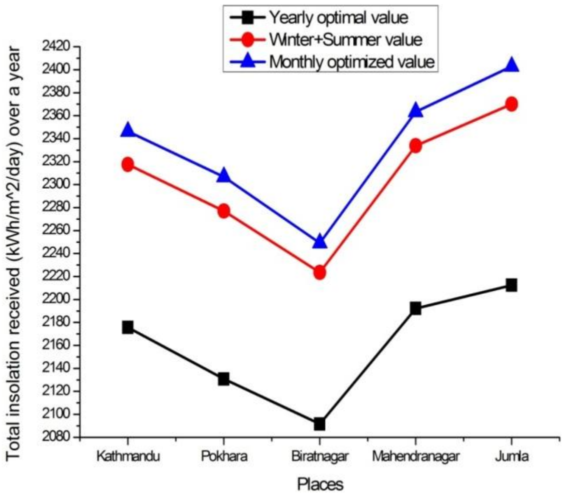

Figure 6: Comparison of insolation based on yearly, monthly and bi-annually

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 insolation 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.

```
function pokhara
DIR=[3.984868035 4.570241158 5.539046921 6.2355
6.483475073 6.027075758 5.325659824 5.010322581
4.814681818 5.073416422 4.476484848 3.978489736];
DIF=[0.453152493 0.53022508 0.664472141
0.806121212 0.948592375 1.025045455 1.106319648
1.071656891 0.932681818 0.673504399 0.512727273
0.435102639];

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)
repmat(DIR(11),1,30) repmat(DIR(12),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)
repmat(DIF(11),1,30) repmat(DIF(12),1,31)];
 %chages latitude
phi=28.23;
%change 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*sind(360*((284+j)/365));
          r1=(-tand(phi)*tand(delta));
          r2=(-tand(phi-k)*tand(delta));
          if (r2<=1 && r2>=-1)
             w=min([acosd(r1) acosd(r2)]);
          else
          w=acosd(r1);
          end
          ws=acosd(-tand(phi)*tand(delta));
%%Uncomment 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*((cosd(phi-k)*cosd(delta)*sind(w))+(pi/180)*
w*sind(phi-k)*sind(delta))/(cosd(phi)*cosd(delta)*sind(
ws)+(pi/180)*ws*sind(phi)*sind(delta)))+DIFFUSE(j)*(
(1+cosd(k))/2)+0.2*GLOBAL(j)*((1-cosd(k))/2);
%           end
         end
   ans(k+1)=sum(H);
    end
      Maxvalue=max(ans)
      Optangle=(find(ans==Maxvalue))-1
```

End

VII. ACKNOWLEDGEMENT

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VIII. NOMENCLATURE

H = daily global radiation incident on a horizontal surface, KWh/m^2/day
H_d = daily diffuse radiation incident on a horizontal surface, KWh/m^2/day
H_s = daily diffuse radiation incident on an inclined surface, KWh/m^2/day
H_T = daily radiation on a tilted surface, KWh/m^2/day
H_R = daily ground- reflected radiation incident on an inclined surface, KWh/m^2/day
H_B = daily direct radiation incident on tilted surface, KWh/m^2/day
β = surface slope from the horizontal, degrees
δ = declination, degrees
ω_s = sunrise hour angle, degrees
ω_s' = sunrise hour angle for a tilted surface, degrees
φ = latitude, degrees
ρ = ground albedo
γ = surface azimuth angle, degrees

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