Solar Radiation Measurements and Model Calculations at Inclined Surfaces

Kazadzis S.1*, Raptis I.P.1, V. Psiloglou1, Kazantzidis A.2, Bais A.3

1 Institute for Environmental Research and Sustainable Development (IERSD), National Observatory of Athens (NOA), Metaxa & Vas. Pavlou, Penteli, 15236, Athens, Greece.
2 Physics Department, University of Patras, Greece
3 Physics Department, Aristotle University of Thessaloniki, Greece

*corresponding author e-mail: kazadzis@meteo.noa.gr

Abstract Inclined panels had been in use to maximize capture of incoming solar radiation. Various approaches are in use for determining of the ideal tilt angle for a specific location according to the latitude and the time of the year. Such algorithms rarely take into account the effect of cloud coverage, which in many cases is an important factor causing large deviations from “cloudless case” theory. A set of four pyranometers, located at National Observatory of Athens at Penteli, had been used to record solar radiation year round. In this study we compare Global Horizontal Irradiance to Irradiance falling at tilted and vertical surfaces. Horizontal surface records agreed with theoretical calculations on cloudless days, absorbing more radiation during summer months but trailing year round to the inclined surface. A more complicated state is observed during cloudy occasions, when the diffuse component of irradiance could lead to higher values of Horizontal Irradiance in wintertime periods, when theoretical calculations predict the opposite.

1 Introduction

Maximizing the portion of incoming solar irradiation by using inclined panels, has been a common practice. Incoming irradiance on a tilted surface can be analyzed in the components of the direct beam irradiation, diffuse irradiation and ground reflectance. Simulating the irradiance on tilted surfaces, when global horizontal radiation (GHI) and diffuse radiation are known, the direct irradiation (DI) can be calculated by the geometrical relation among the surface of interest and the sun angle. GHI on a tilted surface depends on the sun’s zenith angle and the coordinates for each site. A number of approaches had been proposed to calculate the diffuse component, which had been summed up and evaluated by Demain et al (2013). Examining the sun path at a specific location and using each model for the diffuse
component lead to a number of suggestions, which are usually presented as $\phi+15$ (wintertime) and $\phi-15$ (summertime), if a change is possible (Yadav and Chandel, 2013). More changes of slope angle during the year can lead to larger values of absorbed energy (Gunerhan and Hepbasli, 2007). Cloud coverage is the main parameter that leads to different estimations among the various diffuse schemes, ending in different proposed angles (Kelly & Gibson, 2011). In this work we aimed to record incoming irradiance at different angles for large time periods and evaluate the effect of cloud coverage in each case.

2 Data and Methodology

The data set used in this study, was recorded at Actinometric Station of NOA in Pentelh (latitude 38.05°N, longitude 23.86°E, elevation: 500 m a.s.l.), by a set of four pyranometers. The recording frequency was one minute and data are available for 2012 and 2013. The actinometers for measuring the GHI and diffuse horizontal irradiance (DHI) measurements at Pentelh are Kipp-Zonen CM11 pyranometers; in addition, the diffuse radiation is measured by using a Kipp & Zonen shadow ring over the pyranometer. Also a Kipp-Zonen pyranometer is installed facing southward and with an angle of $\beta=38^\circ$ in order to record global irradiation on the suggested by bibliography optimum angle. The last pyranometer was placed vertically facing either west, east, south or north, changing every 10 days. Correction for the dark signal had been made. Data points had been flagged as cloudy or cloudless by using the horizontal irradiance data and a cloudless sky model. Each minute was characterized as cloudy or cloudless and for the characterization of a day as cloudless we chose to assume that at least 70% of the data were characterized as cloud free and total daily radiation was at least 80% compared with the cloudless sky model.

Mean monthly values from the model Photovoltaic Geographical Information System (PVGIS), available from Joint Research center as a web application were used. This model calculates, at 1km x 1km resolution, beam, diffuse and reflected components of the clear-sky and real-sky global irradiation for horizontal or inclined surfaces. The main input parameters to the model are solar radiation from 566 ground meteorological stations containing monthly and yearly averages of daily global irradiation on an horizontal surface, ratio of diffuse to global irradiation and clear sky index. It also takes into account topography (Šúri et al, 2007, Huld et al, 2012).

In addition, we have calculated horizontal irradiance at the sloped surface using recording of GHI and DHI. The direct beam irradiance, is obtained from the measured GHI and DHI (Iqbal, 1983; Psiloglou et al., 1996) using the solar zenith angle of each minute. Reflected from the ground, irradiance, received by the plane of tilt, is calculated (Psiloglou et al., 1996) using a constant ground albedo of 0.2. Then two different approaches are employed for the calculation of the diffuse irradiance received at the sloped surface. The first on used an isotropic model for
the diffuse component, hereafter called ISO. The second one is obtained by using the Hay’s model (Hay, 1979; Hay and McKay, 1988) which uses the total attenuation compared with the extraterrestrial spectrum and the specific tilt angle in order to calculate the diffuse component.

To establish a valid set of measurements for the validation of the ratio GHI / Total-38deg. and also the performance of the HAY/ISO diffuse models the 1-minute mean total and diffuse horizontal irradiance values were compared. A routine quality-control procedure was applied; erroneous data were excluded. The quality tests screened out all (i) diffuse horizontal values greater than 110% of the corresponding total horizontal ones; (ii) total horizontal values greater than 120% of the seasonally correct solar constant; (iii) diffuse horizontal values greater than 80% of the seasonally correct solar constant; (iv) total horizontal values equal to or less than 5 W/m², during sunrise and sunset, due to the pyranometers’ sensitivity; (v) data for a solar altitude less than 5 degrees; and (vi) data with the direct-beam solar component exceeding the extraterrestrial solar irradiance. Results of the comparison of the measured and model values are presented in figure 1 and table 1.

![Figure 1](image)

**Figure 1**: Intercomparison of all (1 minute) values measured at 38° inclination and calculated from HAY model for January (a), March (b), August (c) and October (d), 2012, at Penteli, Athens.

<table>
<thead>
<tr>
<th>Month</th>
<th>RMSE (expressed in % of the Mean Monthly Global Horizontal)</th>
<th>Global Horizontal Mean Monthly value (W/m²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>January</td>
<td>7.11</td>
<td>396.9</td>
</tr>
<tr>
<td>March</td>
<td>4.05</td>
<td>510.9</td>
</tr>
<tr>
<td>October</td>
<td>4.50</td>
<td>469.6</td>
</tr>
<tr>
<td>August</td>
<td>5.04</td>
<td>607.2</td>
</tr>
</tbody>
</table>
3 Results

Averaging year round values for each pyranometer shows that solar zenith angle is the most important factor for calculating incoming irradiation in each case. When cloud free, we can observe the effect of different zenith angles, as expected from the theory, in figure 1a. In figures 1b and 1c, data has been separated according to the cloud flags, we observe that at large zenith angles the appearance of the clouds makes the global horizontal irradiance to have higher values than the incoming on the tilted surface. At the case of vertically placed surfaces, results vary according to the alignments. When the pyranometer is facing eastwards, for a big portion of a day corresponding to early morning hours, it receives more energy than any other placement, even the one inclined at 38° southwards. Obviously after noon, irradiation received at this case becomes quite low. The exact opposite behavior is observed when the vertical surface is facing westwards. In the case of southward facing, a similar in pattern diurnal cycle as in 38° facing, can be noticed. As expected, in the northern hemisphere, the case of a vertical surface facing northwards provides low amount of energy.

![Fig. 2. Year round averaging for every solar zenith angle a) all values b) clear sky c) cloudy d) vertical pyranometer for different orientation.](image-url)

We calculated total irradiation for each day and each facing, by summing up all values. Also the ratio between the GHI and the irradiance at the 38º inclined facing southward surface has been calculated. This ratio provides an easily understood picture of which inclination pattern provides more irradiation in each day including solar position and other atmospheric effects (clouds, aerosols). Clear sky days correlate very well with model estimations, (fig 3) revealing that during summer months the horizontal surface collects more irradiance than the inclined and during winter vice versa. Cloudy days have a more complicated behavior, often changing the dominant inclination. The major factor for this changes are the different cloud
conditions that affect the angle of incidence of solar radiation at each surface by limiting the direct beam and enhancing the part of diffuse radiation on the total incoming radiation. The portion of the direct to total radiation is the dominant factor leading to higher radiation received by the tilted surface compared with the horizontal for winter months (low solar zenith angles). As this portion becomes low due to the presence of clouds, the difference of the solar radiation received on the horizontal and the tilted surface diminish.

A permanent state for cloudy days cannot be resumed, but it appears that during months of expected advantage (winter period) of the inclined surface, in many cases clouds reverses the picture, making an horizontal surface preferable.

PVGIS provides a good picture for the year round behavior of the ratio, but fails to describe deviations, caused by cloud coverage, which is expected using monthly values. Values from HAY and ISO correlate with measurements for the inclined surface very well as seen at fig. 3. Some deviations can be explained from the uncertainty (at least 1 degree) of the positioning of the tilted surface, the constant and spatially independent albedo assumed for the reflectance component and the diffuse radiation model parameterization.

4. Conclusions

Year round fixed inclined surface at 38° leads to higher energy received compared with the one received on a horizontal surface. The experiment that was conducted using measurements of solar radiation for different surfaces (four vertical, one at 38 degrees, a horizontal and the diffuse horizontal), was aiming to compare theoretical climatological model and more sophisticated (using actual horizontal and diffuse
measurements) ones, with actual measurements. We have found a quite good agreement between modeled values and measurements and we tried to assess the effects of clouds on the ratio of the tilted to horizontal surface. The maximization of the incoming solar radiation depends except from the ability to track the sun (or the sun's principle plain), also from the accurate parameterization of the cloudiness which can alter the theoretical excess of the radiation received by a tilted surface compared to the horizontal in wintertime.

Acknowledgments The study has been partially supported by project —Hellenic Network of Solar Energy (HNSE), funded by the General Secretariat for Research and Technology, Greek Ministry of Education,

References


