Evaluating solar radiation on a tilted surfaces – a study case in Timis (Romania)

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Abstract. In the last years the usage of solar energy has grown considerably in Romania, as well as in entire Europe, stimulated by various factors as government programs, green pricing policies, decreasing of photovoltaic components cost etc. Also, the rising demand of using Solar Energy Conversion Systems (SECS) is driven by the desire of individuals or companies to obtain energy from a clean renewable source. In many applications, remote consumers far from other energetic grids can use solar systems more cost-effectively than extending the grid to reach the location. Usually the solar energy is measured or forecast on horizontal surface, but in SECS there is needed the total solar radiation incident on the collector surface, that is oriented in a position that maximize the harvested energy. There are many models that convert the solar radiation from horizontal surface to a tilted surface, but they use empirical coefficients and the accuracy is influenced by different facts as geographical location or sky conditions. Such models were used considering measured values for solar radiation on horizontal plane, in the western part of Romania. Hourly values measured for global solar irradiation on horizontal plane, diffuse solar irradiation on the horizontal plane, diffuse solar irradiation on the horizontal plane and reflected solar irradiation by ground are used to compute the total solar radiation incident on different tilted surfaces. The calculated incident radiation is then compared with the real radiation measured on tilted surface in order to evaluate the performance of the considered conversion models.

1. Introduction

In the last years the usage of solar energy has grown considerable in Romania, as well as in entire Europe, stimulated by various factors as government programs, green pricing policies, decreasing of photovoltaic components cost etc.

In many applications, remote consumers that are located far from other energetic grids can use solar systems more cost-effectively than extending the grid to reach their distant location.

Also, the rising demand of using Solar Energy Conversion Systems (SECS) is driven by the desire of individuals or companies to obtain energy from a clean renewable source.

Usually the solar energy is measured or forecast on horizontal surface, but in SECS there is needed the total solar radiation incident on the collector surface, that is oriented in a position that maximize the harvested energy.

There are many models that convert the solar radiation from horizontal surface to a tilted surface, but they use empirical coefficients and the accuracy is influenced by different facts as geographical
location or sky conditions. Such models were used considering measured values for solar radiation on horizontal plane, in the western part of Romania.

Hourly values measured for global solar irradiation on the horizontal plane, diffuse solar irradiation on the horizontal plane and reflected solar irradiation by ground are used to compute the total solar radiation incident on different tilted surfaces. The calculated incident radiation is then compared with the real radiation measured on tilted surface in order to evaluate the performance of the considered conversion models.

2. Solar energy components

In a point at the top of Earth’s atmosphere, the beam of nearly parallel incident sunrays is referred to as extraterrestrial radiation (ETR). ETR fluctuates about 6.9% during a year (from 1412.0 W/m² to 1321.0 W/m²) due to the Earth’s varying distance from the Sun.

The integration of the extraterrestrial spectrum over all wavelengths defines the solar constant GSC that represents the flux density of incoming solar radiation on a unitary surface perpendicular to the rays at the mean Sun-Earth distance. Since the Sun radiance varies [1], the solar constant does not remain steady over time. There is a variation of about ±1 W/m² around the mean solar constant during a typical Sun cycle of 11 years [2].

Based on data collected over 25 years from terrestrial to space observations, the actual best estimate of the average solar constant is GSC = 1366.1 W/m² [3].

When the solar radiation flux passes through the Earth’s atmosphere, its spectral distribution is modified by absorption and scattering processes.

2.1. Solar energy components

Solar energy reach at photovoltaic panel through different ways as depicted in Figure 1. The most significant quantity of solar energy is provided by the direct radiation that came from the sun, especially on clear sky conditions. Due to various particles presented in earth atmosphere (such as air molecules, dust, fog or cloud elements, drops etc) occurs the diffuse radiation, which become significant in case of cloudy sky conditions. Also the ground surface, including buildings, water surface, vegetation etc, reflects solar radiation that can be collected by a tilted panel.

Figure 1. Solar radiation

In order to be able to analyze the solar radiation incident on a tilted surface is critical to know the surface orientation (azimuth angle and slope angle) as well as the exact geographical position (latitude and longitude) and astronomic time. Thus can be determined important parameters as the zenith angle,
surface azimuth angle, elevation angle $h$ and incidence angle (between sun direction and the normal of the tilted surface) – as depicted in Figure 2. [4]

Figure 2. Tilted surface parameters

The solar radiation can be analyzed considering the following components:

- **Direct beam irradiance** ($G_b$) is the energy flux density (units: W/m²) of the solar radiation incoming from the solid angle subtended by the Sun’s disk on a unitary surface perpendicular to the rays.

- **Direct horizontal irradiance** ($G_h$) differs from the direct beam irradiance in that it is measured on a flat horizontal plane.

- **Diffuse irradiance** ($G_d$) represents the energy flux density of the solar radiation incoming from the entire sky dome on a horizontal surface, excluding the direct beam coming from the Sun’s disk.

- **Global irradiance** ($G$) is the sum of the direct horizontal and diffuse components.

\[
G = G_b + G_d = G_n \cos \theta_z + G_d
\]  

(1)

- **Reflected Irradiance** ($G_r$) is the energy flux density of radiation reflected by the ground that is intercepted by the tilted surface.

- **The total irradiance** ($G_t$) received by a surface tilted with an angle to the horizontal plane is the sum of beam flux density, diffuse flux density, and the reflected flux density $G_r$ of the solar radiation reflected from the ground.

\[
G_t = G_n \cos \theta + R_d G_d + G_r
\]  

(2)
where: $\theta$ is the incidence angle,

$$R_d$$ is the conversion coefficient taking into account the sky view factor and

$$Gr$$ is the energy flux density of radiation reflected by the ground that is intercepted by the tilted surface.

Models for estimating global solar irradiance on tilted surfaces differ generally in their treatment of $R_d$ which is considered the main potential source of errors.

2.2. Solar energy measurement

Solar radiation can be measured using dedicated equipments as pyrheliometers, pyranometers or less expensive equipments as sunshine recorders or even reference PV panels.

The pyrheliometer is used to measure the direct beam radiation, and must be always oriented directly to the sun (see Figure 3). The measurement accuracy is strongly influenced by the sensor characteristics, the performance of the sun tracking system and the dust that cover the lens. [5]

![Pyrheliometer scheme](image)

**Figure 2.** Pyrheliometer scheme

**Figure 3b.** Pyrhielometer

The pyranometer (Figure 4.a) is typically used for measuring the horizontal global radiation, but attaching a sun masking device (solid ring in Figure 4.b, or solid disk with active tracking system in Figure 4.c) can be used for measuring the diffuse radiation. [4][6]

![Pyranometer](image)

**Figure 4a.** Pyranometer (global radiation)

**Figure 4b.** Pyranometer with solid ring (diffuse radiation)

**Figure 4c.** Pyranometer with solid disk (diffuse radiation)

Measurement errors occur in case of dirty lens or improper positioned sun mask (solid ring must be adjusted everyday while solid disk must be adjusted continuously). The ring width or disk diameter also influences the measurement accuracy.
Using PV panels or other chipper equipments for solar radiation measurement will lead to a lower accuracy, which is inadequate for the solar radiation thorough analysis performed in this paper but usually is sufficient for controlling/monitoring the industrial solar energy conversion systems.

3. Solar energy on tilted surfaces

The beam radiation on a tilted surface as depicted in Figure 2 can be relatively easy obtained from measured normal incident beam by applying simple geometrical relations between the horizontal and tilted surface.

\[ G_b = G \cos \theta_c \]  

(3)

Considering that the ground is an isotropic diffuse reflector is possible to determine the ground reflected diffuse radiation incident on a tilted surface, using the Liu and Jordan isotropic formula:

\[ G_r = \rho G \sin^2 \frac{\beta}{2} \]  

(4)

where \( \rho \) is the albedo – ground reflectance.

Because the diffuse radiation arrives from all over the sky with different gradient, the computation of diffuse radiation on a tilted surface is not very simple, existing numerous models that try to correlate the diffuse radiation measured on horizontal surface with the diffuse radiation incident on a tilted surface. The large quantity of such conversion models proves the complexity of this task. [7]

The diffuse radiation \( G_{d,\beta} \) incident on a surface with tilted angle \( \beta \) is:

\[ G_{d,\beta} = G_d \Psi_i \]  

(5)

where \( \Psi_i \) denote a conversion function corresponding to the considered \( i \) model. [8]

In the performed case study there were considered the following models:

- **Liu-Jordan model** – assuming that diffuse radiation is isotropic
  \[ \Psi_{LJ} = \cos^2(\theta_c) \]  

(6)

- **Temps-Coulson model** – assuming clear sky conditions
  \[ \Psi_{TC} = \cos^2\left(\frac{\beta}{2}\right) \left[1 + \sin^3\left(\frac{\beta}{2}\right) \left[1 + \cos^2(\theta) \sin^3(\theta_c)\right]\right] \]  

(7)

- **Hay model**
  \[ \Psi_H = Fr_b + (1 - F) \cos^2\left(\frac{\beta}{2}\right) \]  

(8)

where \( F \) is Hay’s sky-clarity factor defined as \( F = \frac{G_n}{ETR} \) and \( r_b = \max\left[0, \frac{\cos \theta}{\sinh}\right] \)

- **Klucher model** – is a enhancement of the Temps-Coulson model
  \[ \Psi_k = \cos^2\left(\frac{\beta}{2}\right) \left[1 + F' \sin^3\left(\frac{\beta}{2}\right) \left[1 + F' \cos^2(\theta) \sin^3(\theta_c)\right]\right] \]  

(9)

where \( F' = 1 - \frac{G_d}{G} \) is Klucher’s modulating function.
4. Case study

The considered study case was performed for a location from Timis County, in the western side of Romania. There were available data measured in several points from a small area for horizontal global radiation and radiation incident on two tilted surfaces one oriented to South and another oriented to South-West.

The available data measured in horizontal plan was averaged hourly and used for computation of the tilted surface incident radiation, using the four models presented in the above section. Best results were obtained using Klucher model (average error for one year values is less than 4% comparing with measured data on the tilted surface), respectively Liu-Jordan model (average error for one year is less than 6%).

![Figure 5. Solar radiation incident on a tilted surface (January 2012)](image)

Other paragraphs are indented (BodytextIndented style). In Figure 5 there are presented the measured radiation (with blue solid line) on a tilted surface oriented to South-West, for a time period between 10.01.2012 and 17.01.2012 – there can be noticed both cloudy conditions (days 1, 2, 3 and 7) and clear sky conditions (days 4, 5 and 6). The computed values for the tilted surface radiation are depicted with green line (for Liu-Jordan model) and respectively red line (for Klucher model). The model error – difference between model output and the measured data – is depicted with cyan line (for Liu-Jordan model) and respectively magenta line (for Klucher model). It can be noticed a slightly better overall performance of the Klucher model. The abscissa axis represents the day of the year and the ordinate axis represents the incidence solar radiation/error measured in W for a surface of unitary area.
In Figure 6 there are presented the measured and computed radiation on a tilted surface oriented to South-West, for a time period between 19.04.2012 and 26.04.2012. Also in these spring sunny days the Klucher model was more accurate.

**Figure 6.** Solar radiation incident on a tilted surface (April 2012)

In Figure 6 there are presented the measured and computed radiation on a tilted surface oriented to South-West, for a time period between 19.04.2012 and 26.04.2012. Also in these spring sunny days the Klucher model was more accurate.

**Figure 7.** Solar radiation incident on a tilted surface (July 2012)
In Figure 7 is depicted the case of a tilted panel oriented to South, in summer days from 18.07.2012 to 25.07.2012. In this case the Klucher model performances are much better than the Liu-Jordan model.

5. Conclusions
Hourly values measured for global solar irradiation on the horizontal plane, diffuse solar irradiation on the horizontal plane and reflected solar irradiation by ground are used to compute the total solar radiation incident on different tilted surfaces.

The calculated incident radiation is then compared with the real radiation measured on tilted surface in order to evaluate the performance of the considered conversion models. Best results were obtained using the Klucher model.

These models can be used for evaluating the solar potential of a certain location before establish a solar park and also for optimal design of the planned SECS.

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