Determining the Level of Global Solar Radiation on the Earth's Surface

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Abstract. *The article analyzes the Earth's surface insolation. For the analysis, two methods are described - the method of approximate calculation and turbidity method using Linke turbidity index. The methods consider the latitude of current location on the Earth's surface, atmosphere attenuation and other major factors. To obtain more accurate values, long-term measurements at the current location should be obtained.*

Keywords

Insolation of the Earth's surface, method of approximate calculation, renewable energy resources, turbidity method.

1. Introduction

Efficiency of renewable energy sources (RES) is based on the degree of global solar radiation. The most important factor is an insolation, i.e. the incident solar radiation. The remaining components of solar radiation - diffuse and reflected radiation is already affected by the environment and has less impact on overall efficiency. RES are frequently deployed as sources of energy that are based on the use of direct, indirect or mediated sun radiation [13], [14], [15].

Direct and indirect solar radiation is used by solar photovoltaic (PV) cells, the concentration solar photovoltaic cells, solar collectors and concentration solar collectors. Sunlight, stored in other forms of energy, is used in biomass systems, heat pumps, wind turbines, etc. [6], [7], [8], [9], [11]. Geothermal systems have special position - they process the heat generated by the Earth's core. In addition, forming the Earth's core and mantle was also significantly affected by sunlight. This process would have developed quite differently without the sunlight. In addition to RES systems, energy is usually converted and stored during short and long-term periods [1], [2]. Different types of storage systems are a key element of RES. This paper deals with the method of approximate calculation of solar radiation and turbidity method, analyzing direct sun radiation at selected location [5].

2. Method of Approximate Calculation

The method of approximate calculation of direct solar radiation (insolation) is based primarily on an analysis of the position on the Earth's ground, including seas and oceans. Crucial are the geographical coordinates - latitude and longitude of the selected location [3].

2.1. Effect of the Current Location Latitude

The insolation of the active surface is influenced by its position, depending on the latitude. The angle of elevation ϵ is crucial for determining the insolation of the active surface [3]:

$$\epsilon = 90 - \arctan \frac{D_{SZ}}{R_Z \sin \kappa} + \kappa, \qquad (1)$$

where ϵ is the angle of elevation between the sun's rays and the surface normal (°), D_{SZ} is the distance Sun - Earth ($150 \cdot 10^9$ m), R_Z is the radius of the Earth (6378000 m), κ is the angle between the latitude of the sun and the latitude of the active surface (°) and φ is the latitude of the active surface (°).

To determine the average elevation angle κ, we can calculate with the latitude of the current site. As the sun moves from the Tropic of Cancer to the Tropic of

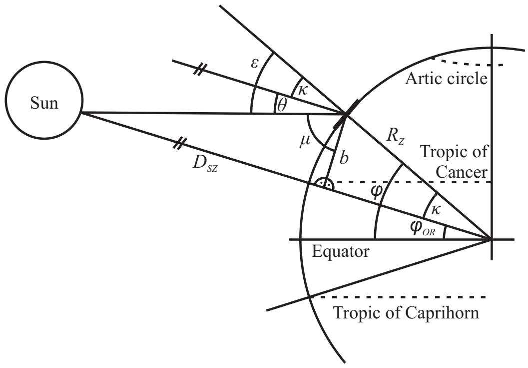

Fig. 1: The current location on the Earth's surface, expressed using the latitude.

Capricorn (and back), polar days and nights are also important phenomenons for locations behind the north and south circle. We can determine κ using the following table (see Tab. 1):

Tab. 1: Determination of κ according to the latitude.

	Tropics	**Temperate zone**	**Frigid zone**
Sun over the Tropic of Cancer	$\kappa = \varphi_{OR} - \varphi$	$\kappa = \varphi - \varphi_{OR}$	$\kappa = \varphi - \varphi_{OR}$
Sun over the Equator	$\kappa = \varphi$	$\kappa = \varphi$	$\kappa = \varphi$
Sun over the Tropic of Capricorn	$\kappa = \varphi - \varphi_{OR}$	$\kappa = \varphi - \varphi_{OR}$	$\kappa = \varphi + \varphi_{OR}$

The exposure of the active surface is variable - when the angle γ increases, the active surface decreases. The insolation can be even zero when the incident radiation is parallel to the active surface (see Fig. 2).

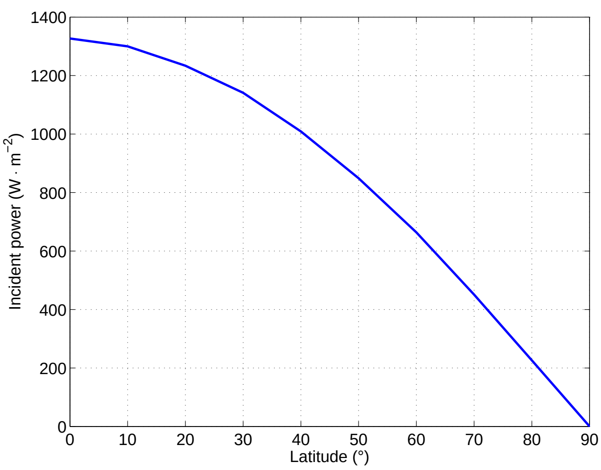

Fig. 2: Insolation affected by the latitude.

2.2. The Influence of the Atmosphere Layer's Thickness over the Current Location

With increasing latitude, the thickness of the atmosphere, through which sun's rays reach the Earth's surface, increases. Also, the height of the sun above the horizon decreases. Therefore, sun's rays have to penetrate the Earth's atmosphere under higher angle and the atmosphere layer appears to be thicker (see Fig. 3).

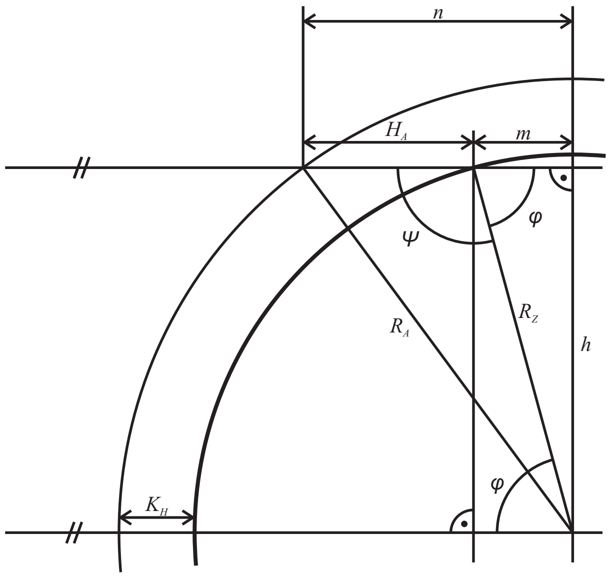

Fig. 3: Effect of latitude on the penetration of sunlight through a layer of the atmosphere.

We assume that the incident rays from the sun are parallel so we can ignore calculation error. At the same time we assume the thickness of the atmosphere of the Earth to be 100 km (Karman line $K_H = 100$ km). Then the radius of the Earth's atmosphere is $R_A = R + 100$ km, i.e. $R_A = 6478$ km [3]. The influence of the thickness of the atmosphere H_A is also dependent on the location according to the value of the latitude φ. From the calculated value H_A, we can consequently calculate the ratio k_P:

$$H_A = \sqrt{R_A^2 - (R_Z \sin\varphi)^2} - R_Z \cos\varphi, \qquad (2)$$

$$k_P = \frac{H_A}{K_H}, \qquad (3)$$

where H_A is the thickness of the atmosphere in the direction of solar radiation (m) and φ is the latitude (°). The parameter k_P expresses attenuation by atmosphere depending on defined latitude (see Fig. 4).

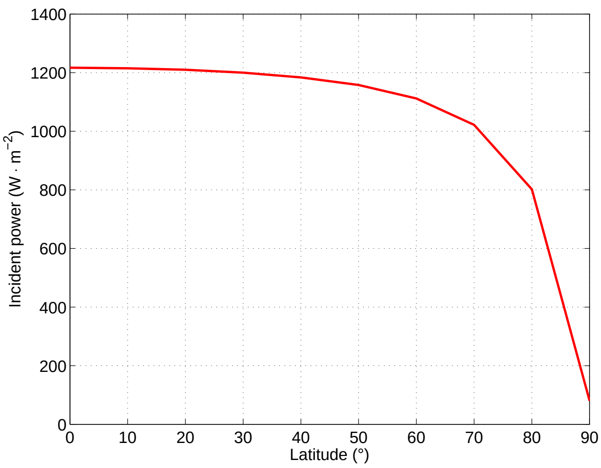

Fig. 4: Attenuation by atmosphere.

2.3. The Influence of Both Factors

The effect of both factors is shown in Fig. 5.

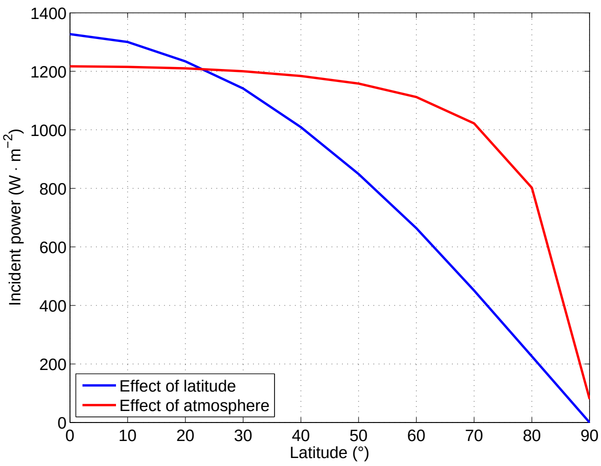

Fig. 5: Effect of both factors - latitude and atmosphere.

2.4. Inclination of the Active Surface of the Solar Panel

Since active surface of solar panel is not always exactly oriented at the sun, it is necessary to consider its azimuth and elevation (see Fig. 6) [4].

The overall efficiency of the solar panel, taking into account elevation, is expressed by:

$$P_{VYR} = P_{DOP} \cdot \cos\Theta, \quad (4)$$

where P_{VYR} is the produced power (W·m^{-2}), P_{DOP} is an incident power (W·m^{-2}) and Θ is an angle between the normal of active surface and the elevation angle of the sun.

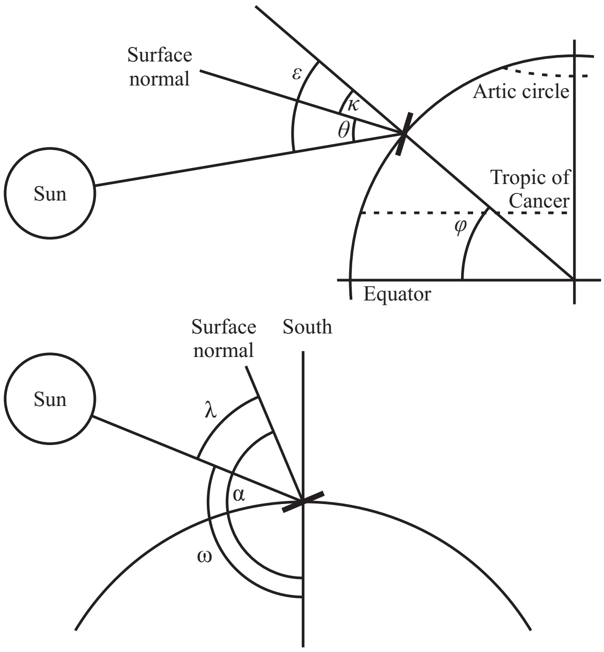

Fig. 6: Active surface of solar panel - elevation and azimuth.

The overall efficiency of the solar panel, taking into account azimuth, is expressed by:

$$P_{VYR} = P_{DOP} \cdot \cos\lambda, \quad (5)$$

where P_{VYR} is the produced power (W·m^{-2}), P_{DOP} is an incident power and λ is an azimuth angle between the normal of the active surface and the azimuth angle of the sun.

The influence of both factors (angle Θ and angle λ) is in Fig. 7.

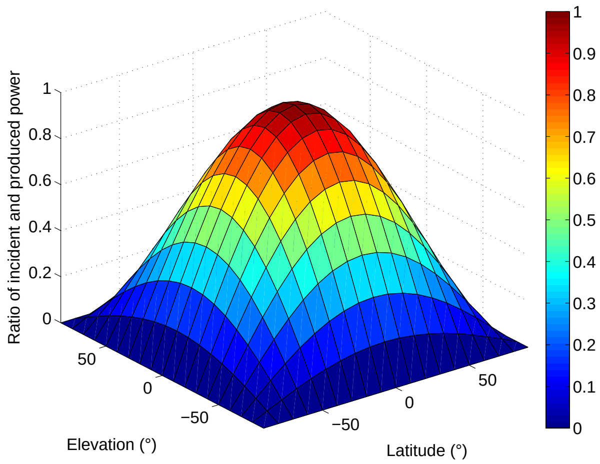

Fig. 7: The influence of azimuth and elevation on produced power.

Angles of elevation (Θ) and azimuth (λ) span from negative to positive values, depending on the orientation of the solar panel in relation to the sun.

2.5. Assessment

The effect of latitude on the insolation can be calculated. This effect, however, can be successfully eliminated by rotating the active surface directly towards the sun. Unfortunately, increasing of the atmosphere layer's thickness with increasing latitude cannot be eliminated. Near the Arctic Circle, the thickness of the atmosphere affects the insolation with a great deal. To obtain maximum amount of produced energy, solar and PV elements are mainly placed on the walls and roofs of buildings, oriented on south. When an optimal orientation is not possible, insolation is affected by the angle between the sun and normal of active surface. This effect can be eliminated using tracker system, which optimizes position of active surface both in elevation and azimuth. On the other hand, these presumptions take into account only ideal weather conditions, not the real effects of weather.

3. Turbidity Method

3.1. How to Calculate Position of the Sun

To calculate amount of sun energy delivered on the Earth's surface, it is necessary to express the angle of incidence of sunlight on the Earth's surface. To determine the current location, the latitude is a key parameter. The angle of incidence is not constant - it varies depending on the season as the elevation angle varies. Nevertheless, we can calculate exact elevation and azimuth with regard to sun position with sufficient accuracy [5]. Declination δ is an angle between the Earth and the direction of the sun's rays expressed by:

$$\delta = 23.45 \cdot \sin(29.7 \cdot M + 0.89 \cdot D - 109), \quad (6)$$

where δ is declination angle (°), M is a number of month, D is a number of a day in a month. To calculate the height of the sun above the horizon, we employ following formula:

$$h = \arcsin(\sin\varphi \cdot \sin\delta - \cos\varphi \cdot \cos\delta \cdot \cos\omega), \quad (7)$$

where h is the height of the sun above the horizon (°), φ is the latitude (°) and ω is the hour angle of the arc in degrees (°) expressed by:

$$\omega = 15 \cdot T, \quad (8)$$

where T is an hour.

Azimuth of the sun can be calculated for either northern or southern hemisphere. We present equations for northern hemisphere, depending on the time of the day. For hours before noon following equation applies:

$$\gamma_S = \arccos\left(\frac{\sin\varphi \cdot \cos\delta \cdot \cos\omega + \cos\varphi \cdot \sin\delta}{\cos h}\right), \quad (9)$$

where γ_S is the azimuth of the sun calculated from the north (°), δ is the declination angle (°), φ is the latitude (°), ω is the hour angle (°) and h is the height of the sun above the horizon (°).

For hours after noon following equation applies:

$$\gamma_S = 360 - \arccos\left(\frac{\sin\varphi \cdot \cos\delta \cdot \cos\omega + \cos\varphi \cdot \sin\delta}{\cos h}\right). \quad (10)$$

3.2. Direct Radiation

To calculate direct radiation IB, it is necessary to know some variables mentioned above and Linke turbidity index [5], expressing air pollution at the current location. Linke turbidity index of air is calculated by long-term meteorological measurements, considering altitude, pollution and type of settlement. However, Linke turbidity index varies throughout the year. In the winter months it's lower and in the summer higher. Following equation expresses direct radiation:

$$IB = \frac{P_{SK}\left(\sin h - \frac{0.1 \cdot T_L(T_L - 1)}{30}\right) \cdot \cos\Theta}{\sin h - 0.106 \cdot T_L}, \quad (11)$$

$$\cos\Theta = \cos\epsilon \cdot \sin h + \sin\epsilon \cdot \cos h \cdot \cos(\alpha - \omega), \quad (12)$$

where IB is direct radiation (W·m^{-2}), P_{SK} is a solar constant (W·m^{-2}), Θ is an angle between surface normal and sun rays (°), h is the height of the sun above the horizon (°), ϵ is an angle between vertical and sun rays (°), ω is an azimuth of the sun (measured from the north) (°), α is an azimuth of normal (measured from the north) (°) and T_L is Linke turbidity index.

3.3. Diffuse Radiation

Diffuse radiation ID is defined as a dispersion of sunlight on the atoms and molecules of the atmosphere and aerosols, suspended in the air [3]. Diffuse radiation IDH (W·m^{-2}) radiating horizontal surface is expressed by:

$$ID_H = \left(P_{SK} \cdot \sin h - \frac{IB \cdot \sin h}{\cos\Theta}\right) \cdot \cdot(0.25 + 0.025T_L). \quad (13)$$

To calculate diffuse radiation on inclined surface ID (W·m^{-2}):

$$ID = \frac{ID_H}{2}\left[1 + \cos\epsilon + \left(0.94 \cdot e^{\cos\Theta} + \frac{1.84}{T_L} - 1.44\right) \cdot \cos\epsilon\right], \quad (14)$$

where ID_H is diffuse radiation on horizontal surface (W·m^{-2}), ID is diffuse radiation on inclined surface (W·m^{-2}), IB is direct radiation (W·m^{-2}), P_{SK} is a solar constant (W·m^{-2}), Θ is an angle between surface normal and sun rays (°) and ϵ is an angle between vertical and sun rays (°).

3.4. Reflected Radiation

The terrain surrounding the irradiated surface is characterized by the reflectance of incident radiation. This value varies from $\rho = 0.90$ (for fresh snow) to $\rho = 0.15$ (for grassy vegetation in summer). Reflected radiation IR (W·m^{-2}) can be expressed by following approximate relation [3]:

$$IR = 0.5 \cdot \rho \cdot (1 - \cos\epsilon) \cdot \left(\frac{P_{SK}\sin h}{\cos\Theta} + ID_H\right). \quad (15)$$

3.5. Total Radiation

The total radiation refers to as global solar radiation. Global solar radiation IG (W·m^{-2}) is the sum of direct and diffuse radiations [3]:

$$IG = IB + ID, \quad (16)$$

and sometimes it is expressed as:

$$IG = IB + ID + IR. \quad (17)$$

The intensity of total solar radiation determines the energy gain of the active surface [3].

3.6. Conclusion

This method deals with the impact of latitude, atmosphere and angle of inclined surface. The influence of the atmosphere is not taken into account - this parameter is replaced by Linke turbidity index. In addition to the calculation of direct radiation, this method also determines the diffuse radiation (diffuse in atmosphere) and reflected radiation (on Earth's surface).

4. Real Situation

Each author uses for his analyses all the available data and values. For example, Halahya had had available data values for Prague, Brno, Bratislava, Kosice, Snezka and Lomnicky stit [3]. Obviously, in these locations Czechoslovak hydrometeorological institute had its own measuring stations. However, how could we evaluate the situation at other locations? For example, there are special maps created by PVGIS [12], showing average values of solar radiation at selected location or country. This kind of map determines the amount of solar radiation, analyzing and showing it on a map in appropriate scale. According to the color scale, it's possible to determine quite quickly average amount of solar energy (kWh·m^{-2}) at different locations. However, these values are just approximate because of two reasons:

- These values were measured during a period from 4/2004 to 3/2010. This time period is quite short, so some corrections would be required. More exact values could be available after measurements during longer periods of time, as year seasons have been slightly changing.
- However, if the statistical evaluations are carried out over a number of years, it would not ensure the refinement of the results. Climatologists note that meteorological situation has been dynamically changing during last years. We can see significant changes in the intervals of weeks. During last 50 years winters were cold and almost constant - roughly from the beginning December until the end of March and summers from June to August. In the last few years, there are almost periodic fluctuations, when in July snows, and December and January are warms (temperatures are very often above zero). Witnesses have certainly noticed that winter turns to summer in a few weeks and a period of gradual warming has almost disappeared. In summer, storms were mild, lasting for 2–3 hours. Usually, when the storm passed, the temperature gradually increased. Nowadays, storms are accompanied by hail, alternatively by tornadoes. In the past, there had been no tornadoes in Europe - now they are very frequent during summer seasons.

The most accurate measurement of the amount of radiation (kWh·m^{-2}) can be obtained during long-term periods. For this reason the RES systems also include sensors for measuring various parameters [10]. The results provide information and an overview of either year period or consecutive years. This kind of analysis provides average results for the current location. This kind of analyse also eliminates the number of factors not provided by special kind of map, mentioned above [12]. For comparison, insulation analysis over three days in July 2007 is presented in Fig. 8.

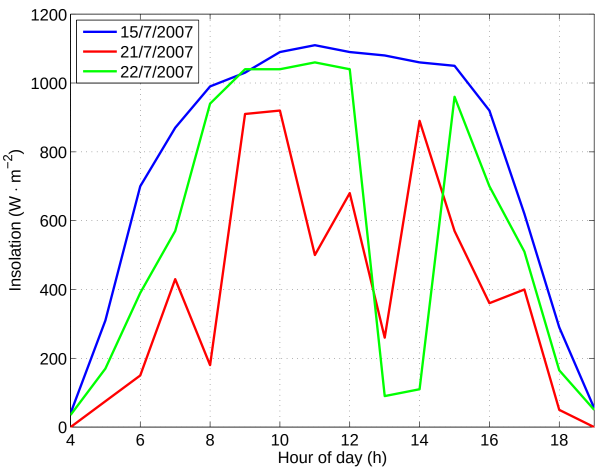

Fig. 8: Insolation during three day period.

On 15th of July 2007, the weather was favorable, and insolation reached relatively high values, without any interruptions. Opposite of this day was 21st of July 2007 - this day was quite misty and partially cloudy. Insolation was quite low. On 22nd of July 2007, measured values were also very interesting. The weather was favorable, except for higher humidity, slightly decreasing insolation. From about 1 PM until 2 PM, there was a storm, causing significantly decreased insolation. After finishing this storm, the insolation partly increased. To demonstrate basic calculations of insolation, there is a Tab. 2 providing basic amounts of insolation and produced energy for these days.

Tab. 2: Insolation during selected days.

Date	Insolation (kWh·m^{-2})
15/7/2007	12.305
21/7/2007	6.375
22/7/2007	8.870

During a sunny day insolation can reach a value of 12.305 kWh·m^{-2}. In case of mist or clouds, insolation drops significantly, perhaps by half or more. However, there are some days with dynamic weather changes, like 22nd of July 2007 - almost all day was sunny, but when storm came, insolation was reduced to a very small value.

Solar panels can be installed in two ways. Firstly, they are fixed to different surfaces having constant orientation in relation to the sun. Constructions can be deployed on Earth's surface, or fixed to the walls or roofs. Another option is using of a tracker system, providing higher efficiency. According some data provided by the producers, overall efficiency can by increased even by 30 %. In this case, the angles between surface normal and the sun (Θ and λ) are constantly evaluated and minimized. However, this type of implementation is rather costly.

5. Conclusion

Calculation of global solar radiation, i.e. insolation of the Earth's surface, seas and oceans was analyzed by two methods:

- Method of approximate calculation, based on latitude and longitude of current location, influencing overall insolation.
- Turbidity method, taking into account Linke turbidity factor.

To obtain more accurate results, it is better to replace approximated values of insolation with the results of long-term measurements at selected location. If all factors are taken into account, predictions of insolation for selected location will be more accurate and reliable.

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Miroslav DULIK graduated in 2000 as an electrical engineer at the Academy of Armed Forces in Liptovsky Mikulas. In 2005 he finished his Ph.D. studies. He has specialized in microprocessor programming and computer networks. Since 2008 he has also interested in controlling systems for renewable energy sources, trying to develop new concepts and solutions, optimizing overall performance.