Potential Solar Irradiance Assessment based on a Digital Elevation Model

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***Abstract*—The sun is an extremely powerful energy source and solar radiation is by far the largest source of energy received by the earth. Assessment of solar radiation can be based upon measured data, where are available, or results of mathematical models. In this paper is presented a model, developed on the clear sky conditions, which allows calculation of solar radiation intensity at any location on the earth surface, considering the geographical coordinates of location and local time of every day of the year. Based on the SRTM database, in the paper it is developed a digital elevation model, which together with presented model allows computation of the potential of solar radiation over the Iasi county territory. For validation, the results have been compared with data obtained from SoDa project, the results from both database being fairly close, these proving satisfactory accuracy for a preliminary evaluation of solar radiation.**

***Index Terms*—solar energy, global solar radiation, digital elevation model.**

I. Introduction

During the last decades, a growing interest for solar energy systems has been observed. The solar energy system includes that technology which converts the solar energy in a useful form of energy. Among these technologies, the most widely used solar energy systems include the photovoltaic panels and the thermal collectors.

Essential steps required for effective planning and designing of a solar energy system depend on adequate information of the solar radiation on the region or location of the system placement. The best information about solar radiation is obtained from experimental measurement on location of system placement but, the mathematical models can provide adequate information. The mathematical models provide sets of equations that can be used to predict where the sun is in the sky at any time of day and any day of year, for any location on earth, as well as the solar radiation intensity.

Solar energy systems must be planned and designed taking into account the highest solar energy input that can be received by the system, usually received under the clear-sky condition. Thus, in this paper, a deterministic model of solar irradiance is presented, considering the assumption of the clear sky conditions.

The aim of this paper is to compute the potential solar radiation, over Iasi county territory, using the digital elevation, latitude and longitude data. Therefore, in the paper, a mathematical model for solar radiation is described and adapted in accordance with a digital elevation model (DEM) of Iasi territory, in order to generate a potential solar power database. For validation, the results are compared with data obtained from Solar Radiation Database for Environment (SoDa) services [16], which express the intensity of solar radiation at ground level by processing collected satellite information. The comparative results show that the potential solar radiation database has a satisfactory accuracy and, therefore, it can be used as a practical tool for an interpretation of the potential of solar radiation for any given location from analyzed territory.

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II. Clear Sky Global Irradiance Model

According with the terminology used in the solar energy field, we have to make the difference between following two terms for solar radiation: irradiation and irradiance. The amount of energy received by the earth from the sun rays, which fall on a unit surface on the ground, is defined as the irradiation, H (Wh/m^2). Since energy is power integrated over time, an instantaneous quantity is measured by power density of solar radiation, defined as the irradiance. The irradiance, G (W/m^2), is the rate at which the solar energy is incident per unit area of a surface, in a unit time.

The amount of irradiance received on particularly location of the earth's surface depends on three main factors, namely: the irradiance values outside of atmosphere, the attenuation effects of the earth's atmosphere, and the daily and hourly position of the sun relative to the location from the earth.

Outside the earth's atmosphere, at any given point in space, the irradiance received from the sun is nearly constant. The average of irradiance at the top of the atmosphere is defined as the solar constant, G^{S0} (W/m^2). The solar constant is a measure of the energy amount received per a unit area of a surface perpendicular to the direction of the sun rays' propagation in a unit time, and is adopted to be equal to 1367 W/m^2 [1]–[4].

Because the earth revolved around the sun in an elliptical orbit, the distance between the sun and the earth is in a continuously changing. As a consequence, the irradiance outside of earth's atmosphere fluctuates around of solar constant value during a year. Since the astronomical position of the earth to the sun is known, the extraterrestrial irradiance value for a given day of the year can be evaluated using following relationship [1]–[4]:

$$G^{E0} = G^{S0} \cdot \left[1 + 0.034 \cdot \cos\left(\frac{2\pi}{365} (N_d - 1) \right) \right] \qquad (1)$$

where: G^{S0} is the solar constant and N_d is the number of the day in a year, corresponding to a given date (i.e., first day for 1 January and the 365th day for 31 December).

When the solar radiation passes through the earth's atmosphere, it is reduced due to reflection, scattering and absorption, thus, the irradiance that reaches the earth's surface is much reduced in intensity. The radiation that is not reflected or scattered and directly reaches on the earth's surface is known as direct (beam) radiation, G_D (W/m^2), while the scatter radiation that reaches the ground is called diffuse radiation, G_d (W/m^2). Therefore, at ground level, the irradiance that reaches on the ground horizontal plane is obtained from both direct and diffuse components of global irradiance.

A literature survey indicates different parametrical and empirical models for both components of solar radiation, as for direct component of the radiation can be used the model (known as the Kreith's model) presented in [4], [6], while for the diffuse component is used the model developed in [7], which together generated a properly model for the irradiance on a horizontal plane. The Kreith's model includes a set of empirical equations, developed in the assumption of clear sky conditions, which take into account the zenith angles as well as the atmospheric transmittance, being stated on following equation:

$$G_D = G^{E0} \cdot \tau_D \cdot \cos(\theta_Z) \quad (2)$$

where G^{E0} is the extraterrestrial irradiance on the N_d th day of year, evaluated with eq. (1), τ_D is the atmospheric transmittance, and θz is the zenith angle.

The atmospheric transmittance accounts the effects of the earth's atmosphere on the direct solar radiance [4], [6], in accordance with eq. (3), being affected through the air mass ratio, m, by two main factors, namely the direction of the sun's rays and the local elevation, as is expressed in eq. (4).

$$\tau_D = 0.56 \cdot \left(e^{-0.65 \cdot m} + e^{-0.095 \cdot m} \right) \quad (3)$$

The air mass is approximated by Kasten's formula [3],[8]:

$$m = \frac{1 - 10^{-4} \cdot z}{\cos(\theta_Z) + 0.50572 \cdot (96.07995° - \theta_Z)^{-1.6364}} \quad (4)$$

where z is the elevation of the observer location relative to the sea level, in meters, and the zenith angle, θ_Z, is expressed in degree.

Diffuse component of solar radiation, on a horizontal plane and under clear sky condition, can be calculated using the model presented in [7] (known as the Gates's model), which is related to atmospheric transmittance by the following equation:

$$G_d = G^{E0} \cdot (0.271 - 0.294 \cdot \tau_D) \cdot \cos(\theta_Z) \quad (5)$$

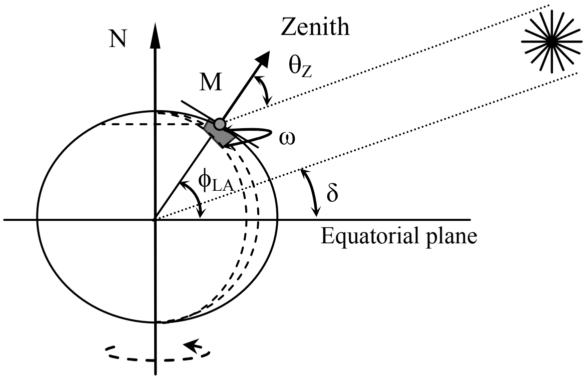

Figure 1. The relative position of the location to the sun.

The zenith angle represents the angle between the rays of sun and the vertical direction (normal to the surface) at a ground plane, as is depicted in Fig. 1. The zenith angle is related to the angles of latitude, the earth's declination and the hour angle by the following relationship [1]–[5]:

$$\cos(\theta_Z) = \cos(\phi_{LA}) \cdot \cos(\delta) \cdot \cos(\omega) + \sin(\phi_{LA}) \cdot \sin(\delta), \quad (6)$$

where ϕ_{LA} is the latitude angle of the observer location, δ is the earth declination angle and ω is the hour angle.

The latitude of a location on the earth is the angular distance of the observer location to the equator. The latitude is an angle and is usually measured in degree, but in eq. (6) must be converted in radians.

The solar declination angle represents the angle between sun rays and the equatorial plane, gradually changing from +23.45° (or north) on June 21, when earth's axis is tilted toward the sun, to -23.45° (or south) on December 21, when earth's axis is tilted away from the sun. The declination angle can be found from following equation [1]–[5]:

$$\delta = 23.45 \cdot \frac{\pi}{180} \cdot \sin\left[\frac{2\pi(N_d - 81)}{365}\right] \quad (7)$$

The hour angle describes, in number of degrees, how far the sun is from the local meridian, decreasing with 15° per hour, from positive values in the morning to negative values in afternoon. It is zero when the sun is directly over local meridian (overhead at the solar noon). In other words, the hour angle is the difference between noon and the desired time of the day, expressed in terms of a 2π rotation in 24 hours, as in eq. (8), where t_{ST} is the solar time:

$$\omega = \frac{2\pi}{24} \cdot (12 - t_{ST}) \quad (8)$$

The solar time is a correction applied to the local zone time, considering the rotation of earth about its axis and, also, the earth's revolution around the sun. The correction of local zone time has two components. First, there is a correction for the difference between the local time meridian of the local zone time and the observer's meridian (longitude). The second correction takes into account the perturbations in the earth revolution around the sun during which the earth does not sweep equal areas [5].

Each time zone is assigned with a local time meridian. Solar noon occurs at 12 noon at only local time meridian. At longitudes east of local time meridian, solar noon will occur before 12 noon and at longitudes west of them, solar noon will occur after 12 noon. For instance, the Romanian local time meridian is 30° east, thus, for Iasi city, having the longitude as 27°35' east, the sun will be at solar noon an average of 9.67 minutes later than local zone time noon (12.00 PM considering the civil clock time). The solar time, t_{ST} (hour), is related to the local zone time, t_{ZT}, through the following equation [1]-[5], having in view the above corrections:

$$t_{ST} = t_{ZT} - DST + \frac{\phi_{LT} - \phi_{LO}}{15} + ET \quad (9)$$

where ϕ_{LT} is the local time meridian for the local time zone, ϕ_{LO} is the longitude of the observer location, DST is the daylight saving time and ET is the equation of time. To local time meridian, the difference between solar and local zone times is defined as the equation of time, in hours, which is expressed in [1] as:

$$ET = \frac{9.87}{60}\cdot\sin\left(2\cdot\frac{2\pi(N_d-81)}{365}\right)-\frac{7.53}{60}\cdot\cos\left(\frac{2\pi(N_d-81)}{365}\right) -\frac{1.5}{60}\cdot\sin\left(\frac{2\pi(N_d-81)}{365}\right) \quad (10)$$

Considering equations (1-10), it follows that if the latitude, the longitude and the elevation of a given location are known, the irradiance for that location, in a clear sky condition, can be theoretically predicted for a given time of the day, and for a given day of the year, respectively.

III. Potential Solar Radiation Evaluation

In order to create a potential solar radiation database for Iasi county territory, a DEM has been developed and used as input argument in an applications tool developed on Matlab software and based on previous model. A DEM is a three-dimensional model of the earth's surface, provided in digital form, containing the latitude, longitude and elevation data for any point on earth surface.

For a DEM at a medium resolution for Iasi county, which to be used in potential solar modeling, it has been chosen to extract the earth's surface information from the Shuttle Radar Topography Mission (SRTM) database. The SRTM is a joint international project developed by National Aeronautics and Space Administration (NASA) and the National Imagery and Mapping Agency (NIMA), whose main objective is to generate a near-global digital elevation model of the earth using radar interferometry [12]. The SRTM database is a non-commercial product and is freely available at the USGS EROS Data Centre [13] for download. These data are intended for use with a Geographic Information System or other special application software, and are not directly viewable in a browser. The original data have a resolution of 3 arc-sec (approximately 90 m). High resolution SRTM database (1 arc-sec, about 30m) is available only for the United States and other few countries. More information about the SRTM can be found in [12]–[14].

Iasi county is located between 46°49' and 47°35' north latitude parallels, and between 26°28' and 28°11' east longitude meridians. For these coordinates, there were downloaded 6 hgt.zip files from [13], covering different areas by files with the name that includes an extension of 1° latitude and 1° longitude situated between 46N-47N lines and 26E-29E lines, those indicating the latitude and the longitude of the area. For instance, the N46E027.hgt.zip includes the area between 46° and 47° north latitudes, respectively 27° and 28° east longitudes.

A function in Matlab software has been involved to draw out from the SRTM files (with 3 arc-sec resolution) the data in the DEM format. The function needs as input arguments the decimal degree coordinates and it has as output argument the geographical coordinates in the longitude / latitude / elevation format.

Although the initial resolution was approximately 90 m, the resolution of our DEM model has been chosen to be in a step of 0.01° longitudes and latitudes, between 26.45° and 28.20°, respectively 46.75° and 47.60°, meaning 175×85 cells with the same elevation value, even a DEM with a higher resolution can be obtained. The resolution of resulted DEM is about 1km × 1km, being enough for this paper aims, the Iasi county territory being presented in Fig. 2.

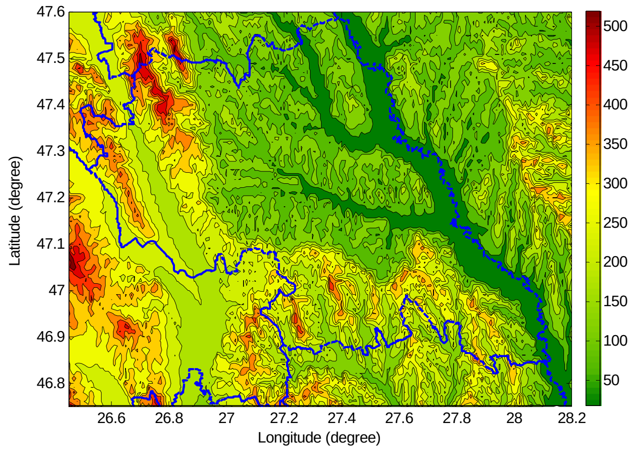

Figure 2. DEM of the Iasi county territory.

A Matlab application, having as input parameters the latitude, longitude and elevation of the location, respectively the day number and the local time, has been developed and used together with the DEM of Iasi county. The application estimates the direct and diffuse components of the clear sky global irradiance on a horizontal surface, the results being graphically represented, as in Fig. 3 (for June, 21), or tabulated for given coordinates.

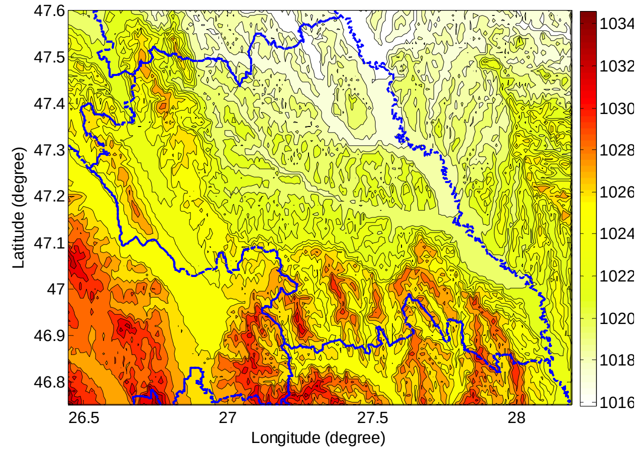

Figure 3. Irradiance solar map for Iasi county (on June, 21).

For validation of application results, a research of other radiation models is required. Various database and estimation tools are available worldwide, significant progress being made in this direction in last time [9]-[11]. In [10] is presented a state of art regarded by the evolution of solar radiation projects in last time, among of these may be mentioned European Solar Radiation Atlas, SoDa, Meteonorm, NASA SSE, Satel-light, etc. A last model, based on the recent works in the field, has been used in the Integration and Exploitation of Networked Solar Radiation Databases for Environment Monitoring project [15], the database can be accessed through SoDa services [16], where most of the results are available in the graphical or tabular form.

In order to validate the developed potential solar radiation database, the application results have been compared with typical irradiance values given by the SoDa services. Therefore, the solar irradiance has been calculated for five location of Iasi county, at the equinoxes, on March 21 (N_d=80) and September 23 (N_d=266), respectively at the solstices, on June 21 (N_d=172) and December 21 (N_d=355). The five locations have been chosen to cover whole Iasi county territory.

The comparison of irradiance values from SoDa database with that computed from our application, for Iasi city, are presented in Fig. 4, where in the bar graph are presented our results and in the stairs graph, the SoDa values.

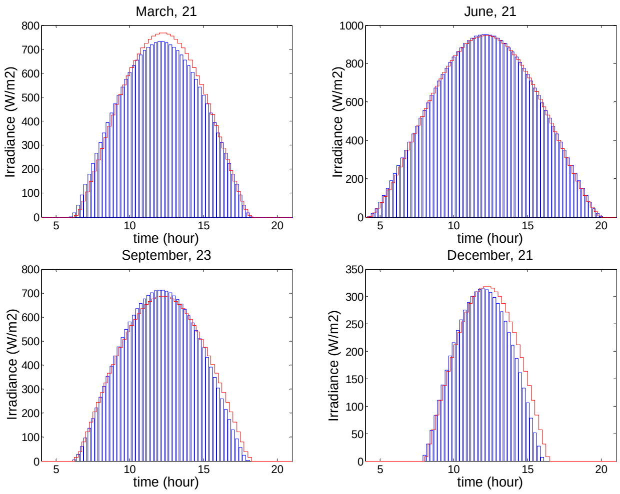

Figure 4. Comparison of global irradiance variation in time.

The degree of accuracy of developed model is evaluated by two statistical tests, mean bias error (MBE) and root mean square error (RMSE) [3]. To obtain dimensionless statistical indicators, the MBE and RMSE have been normalized to average of global irradiance, the percentage of relative errors being calculated and presented in Table 1.

TABLE I. PERCENTAGE MBE AND RMSE FOR FIVE LOCATIONS

Location DEM information Date		Iasi 47.16°N 27.58°E 43 m	Pascani 47.23°N 26.72°E 246 m	Tg. Frumos 47.2°N 27°E 100 m	Harlau 47.42°N 26.9°E 174 m	Lespezi 47.35°N 26.68°E 214 m
March, 21	MBE	0.54	-1.44	0.22	0.04	-1.57
	RMSE	6.65	5.89	6.47	6.40	5.86
June, 21	MBE	5.48	3.16	5.05	4.64	2.70
	RMSE	8.68	4.63	8.22	7.79	5.96
September, 23	MBE	- 0.25	-0.09	0.37	0.17	-0.62
	RMSE	5.67	5.70	5.96	5.87	5.50
December, 21	MBE	- 5.09	-5.89	-4.06	-4.66	-6.05
	RMSE	11.93	12.54	11.33	11.74	12.73

The MBE provides information about the model's performance, a lower MBE value being desirable. A positive value indicated overestimated values, while a negative values, an underestimated value. The RMSE is always positive, and a lower value is desirable, too. RMSE test provides information about the deviation between the calculated values and the SoDa values.

As can be seen in Table 1, it can be stated that the model gives fairly close results for a preliminary evaluation of solar intensity radiation. The percentage of MBE for all locations under consideration varies from 0.09 to 6.05 %, while RMSE varies from 4.63 to 12.73 %. The percentage values of BME are relative low, especially at equinoxes, indicating a good agreement with the SoDA data.

From comparison, we founded similar types of variation for all location in the June and December months, when the percentage values of errors appear relative larger. Thus, the model results are underestimated with about 5.15 % in December, and overestimated with about 4.2 % in June, one of the reasons being the use of simplistic models for direct and diffuse components of solar radiation, in comparison with the techniques used in SoDa project. Consequently, the obtained database has a satisfactory accuracy, comparable to the instrumental measurements, which can be used for a faster preliminary evaluation of the irradiance over the Iasi county territory.

IV. CONCLUSION

Measurement and modeling of intensity solar radiation is an important factor for the evaluation and deployment of solar renewable energy systems. The method presented in the paper is a simple solar radiation model, which can be easily integrated with a DEM for a relative accurate and fast estimation of solar irradiance over whole analyzed territory. The main advantage of the method, compared with other solar radiation estimation tools, is the estimation of database in a three-dimensional format, for any moment time, being easily analyzed in both graphical and numerical formats.

In the future works, the method will be improved to calculate, as an interactive application, the irradiance as well as the irradiation, and joined with an extended DEM to compute the potential solar radiation over Romanian territory.

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