Sustainability **2015**, *7*, 2644-2661; doi:10.3390/su7032644

OPEN ACCESS

sustainability

ISSN 2071-1050

www.mdpi.com/journal/sustainability

Article

Estimating Solar Irradiation Absorbed by Photovoltaic Panels with Low Concentration Located in Craiova, Romania

Ionel L. Alboteanu *, Cornelia A. Bulucea † and Sonia Degeratu †

Department of Electromechanics, Environment and Industrial Informatics, Faculty of Electrical Engineering, University of Craiova, Craiova 200440, Romania;
E-Mails: abulucea@em.ucv.ro (C.A.B.); sdegeratu@em.ucv.ro (S.D.)

† These authors contributed equally to this work.

* Author to whom correspondence should be addressed; E-Mail: lalboteanu@em.ucv.ro;
Tel.: +40-251-435-724; Fax: +40-251-435-255.

Academic Editor: Nikos E. Mastorakis

Received: 13 January 2015 / Accepted: 13 February 2015 / Published: 4 March 2015

Abstract: Solar irradiation is one of the important parameters that should be taken into consideration for the design and utilization of a photovoltaic system. Usually, the input parameters of a photovoltaic system are solar irradiation, the ambient environment temperature and the wind speed, and as a consequence most photovoltaic systems are equipped with sensors for measuring these parameters. This paper presents several mathematical models for solar irradiation assessment. The starting point is represented by the mathematical model of extraterrestrial irradiation, and resulting finally in the model for solar irradiation, absorbed by a low concentration photovoltaic panel. These estimating models of solar irradiation have been particularized for the Craiova, Romania, and have been verified through numerical simulation. Regarding terrestrial solar irradiation, four mathematical models have been adopted, namely Adnot, Haurwitz, Kasten and Empirical (EIM). Of these, the most appropriate for the Craiova location were the models Adnot and Empirical. Consequently, for the calculation of the solar irradiation absorbed by the photovoltaic (PV) panels with low concentration, these models have been taken into consideration. In this study, a comparative analysis was also carried out with respect to the solar irradiation absorbed by the PV panels without concentration and those with collectedness of the solar radiation. This analysis was based on the results of numerical simulation and experimental tests.

Keywords: low concentrating photovoltaic system; mathematical models; photovoltaic panel; solar irradiation

1. Introduction

Over the last decades, because of pollution and awareness of limited resources of fossil fuels, renewable sources of energy production gained increasing confidence as an appropriate solution for humankind.

Within the southern region of Romania, due to the high solar potential, numerous photovoltaic stations have been developed. Still, one could note that these solar plants take up a considerable amount of agricultural land.

This paper is the starting work for a study that aims to address meaningfully the issues of increasing efficiency of photovoltaic systems with the utilization of solar radiation concentrator elements, as well as reducing of costly photovoltaic surface.

Analysis of a conversion system for solar energy to electric energy is based on an accurate assessment of solar radiation in the given location. Hence, aspects of solar radiation properties should be known [1,2], as well as aspects regarding astronomical data [3].

Regarding the calculation of solar irradiation absorbed by a low concentration photovoltaic panel (LCPV), in the literature [4–8], these aspects are approached, but with values and particularities for certain locations submitted to study.

2. Modeling and Simulation of Solar Irradiation

In order to get to the mathematical model of solar irradiation absorbed by a photovoltaic panel provided with a low radiation concentration system, one could start from the mathematical model of extraterrestrial irradiation.

2.1. Extraterrestrial Irradiation

Although in some models from the literature the extraterrestrial solar radiation is considered constant [9], the model of extraterrestrial solar radiation for a certain location could be expressed by the relation below:

$$G_0 = \frac{24}{\pi} \cdot S \cdot \left[1 + 0.33 \cdot \cos\left(\frac{2\pi \cdot n}{365}\right)\right] \cdot \left(\cos\phi \cdot \cos\delta \cdot \sin\omega_s + \omega_s \cdot \sin\phi \cdot \sin\delta\right) \ [\text{W/m}^2] \quad (1)$$

where:

S is the solar constant;

n is the days’ number of the year;

φ is the latitude of the considered location;

δ represents the declination of the Earth;

and ω_s is the solar angle.

Particularizing the mathematical relationship (1) for Craiova, Romania as the location (φ = 44.3°) it resulted in the diagram of extraterrestrial irradiation evolution over the course of a year (see Figure 1).

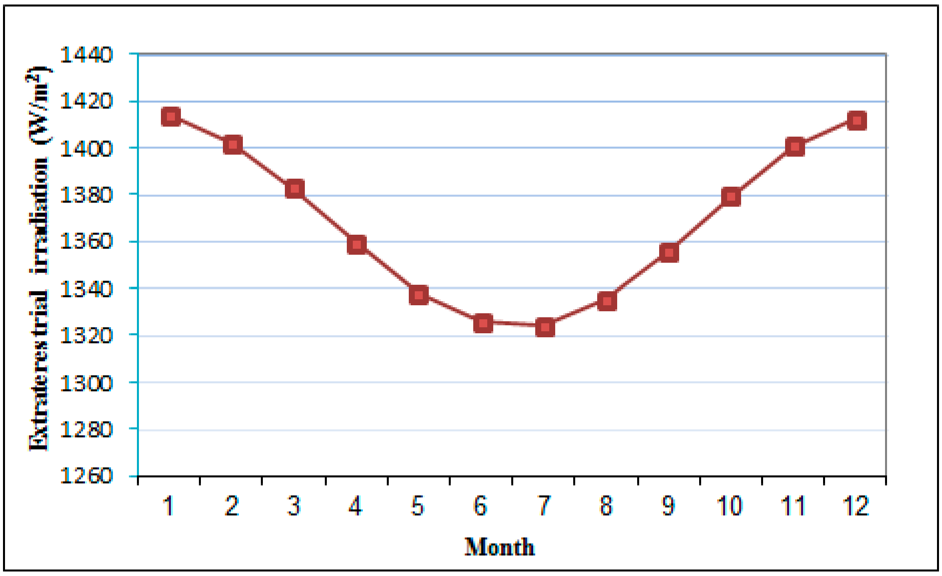


Figure 1. Chart of annually extraterrestrial irradiation for Craiova location.

As can be seen in Figure 1, the extraterrestrial solar irradiation particularized for a certain location is not constant over the duration of an entire year.

Influence of atmosphere

The air mass m characterizes the path travelled by the solar ray through the atmosphere to the sea level. One could note that $m = 0$ for the extraterrestrial space or if the Earth would be without atmosphere. In the equatorial area, when the sun is in the zenith, the solar ray travels the shortest distance, meaning $m = 1$. For zenith angles θz (by zenith angle one could mean the angle between the location vertical and the direction towards the sun) from 0° to 70° the air mass m can be calculated using the expression below:

$$m = \frac{1}{\cos\theta_z} \tag{2}$$

If θ_z is equal to 60°, then the air mass m = 2, *i.e.*, the solar ray will travel a path through atmosphere 2 times higher than for $\theta_z = 0°$. In the second situation the solar ray will be more attenuated and will transport less energy. This way could be explained the decrease of the solar radiation intensity in the north and south hemispheres, respectively, in comparison with the equatorial zone.

2.2. Terrestrial Irradiation

Information on solar irradiance on the earth's surface is necessary for application of solar energy, for the determination of the amount of spectral global irradiance for the photovoltaic cells designing and for the selective absorbers for spectral thermal collectors [10–12].

Solar radiation estimation has been carried out from the very beginning of operation of solar converters in order to guide scientific and commercial applications [13]. In this sense, the main interest is in estimating the solar irradiation collected on tilted surfaces, for which the usual numerical estimation is based on global and diffuse radiation on a horizontal plane [13].

Before describing the mathematical models for solar radiation assessment, one could emphasize some notions of celestial mechanics which describe the position of the sun in a sky roof at every moment (see Figure 2).

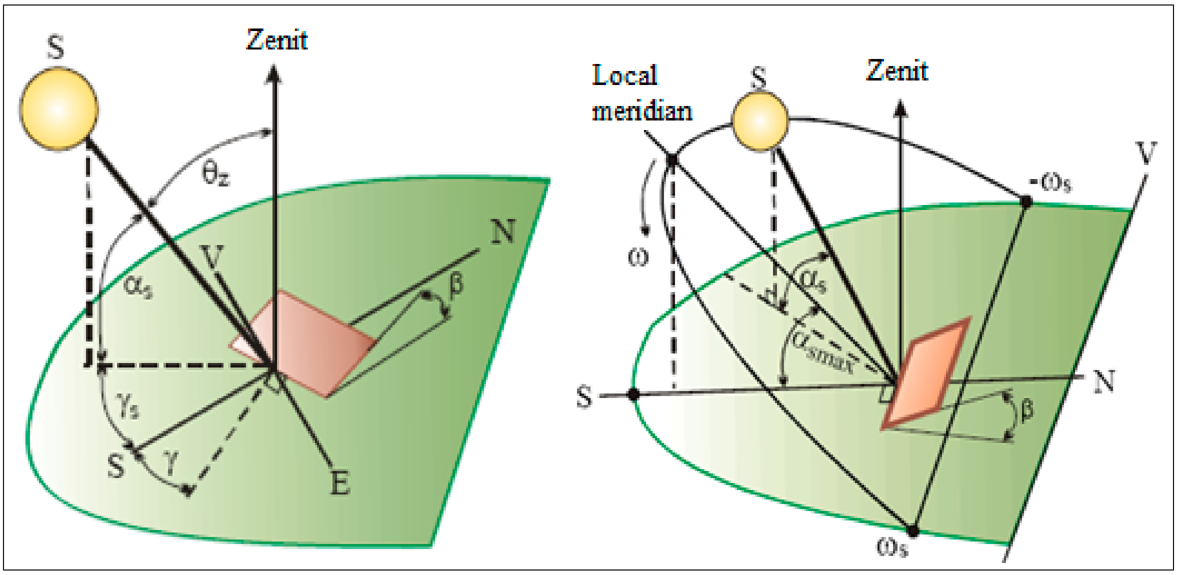


Figure 2. Parameters describing the sun position in sky roof, according to [14].

It is obvious that in one hour the sun travels in the sky an angle equal to 15°, and its position at any time T can be expressed by the relationship below:

$$\omega = 15 \cdot (12 - T) \tag{3}$$

If the angles δ, φ and ω are known, it can easily be determined what the sun position in a sky roof at a particular point is, for any hour and any day, using the expressions below [15]:

$$\sin \alpha_s = \sin \delta \sin \varphi + \cos \delta \cos \varphi \cos \omega = \cos \theta_z \tag{4}$$

$$\cos \gamma_s = \frac{\sin \alpha_s \sin \varphi - \sin \delta}{\cos \alpha_s \cos \varphi} \tag{5}$$

In relationship (4) if the condition $\alpha_s = 0$ is imposed, and one could calculate the horary angles of sunrise and sunset, respectively, by using the relationship:

$$\omega_s = \pm \cos^{-1}(-\tan \varphi \cdot \tan \delta) \tag{6}$$

For any day of the year, from (6) for the particular hour T the horary angle ω can be determined, and knowing the site latitude φ, the elevation angle of the sun α_s might also be determined.

One could remind the reader that the total number of irradiation incidents on the surface of a body on Earth is equal to the sum of direct, diffuse and reflected components of irradiation (see Figure 3).

$$G_g = G_D + G_{dif} + G_R \tag{7}$$

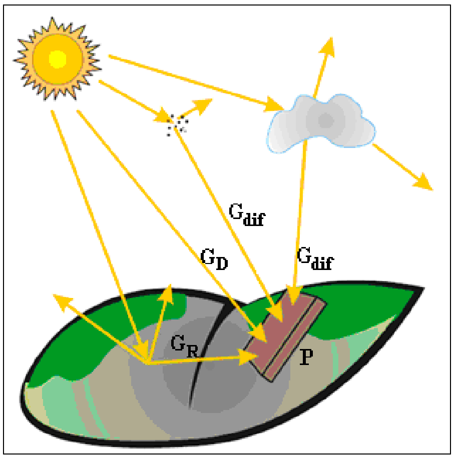


Figure 3. Components of solar irradiation according to [13].

The simplified models of irradiation are empirical models resulting after fitting of a set of measurements, usually from a single location, which restricts their scope of applicability. This is an obvious disadvantage compared with the parametric models, which have a physical basis in spectral patterns, and the input parameters give them a generality trait. Still, the empirical models are commonly used in practice due to their simplicity. Further, we will be present some of these models, available under a clear sky.

In literature, one can find several models to determine solar irradiation, still in this study, some empirical models for estimating the solar irradiation specific to a certain location are particularized, as follows below.

- Adnot model, which models global solar irradiation under conditions of a clear sky, by using the relationship [9]:

$$G_g = 951.39(\sin\alpha_s)^{1.15} \ [\text{W/m}^2] \tag{8}$$

This pattern has been verified using the meteorological data of Romania collected from the meteo stations of the Romanian capital Bucharest, and the Romanian cities of Iasi, Craiova, Timisoara and Constanta [9].

- Haurwitz model [9].

$$G_g = 1098 \cdot e^{\frac{0.057}{\sin\alpha_s}} \cdot \sin\alpha_s \ [\text{W/m}^2] \tag{9}$$

- Kasten model [16]

$$G_g = 910 \cdot \sin\alpha_s - 30 \ [\text{W/m}^2] \tag{10}$$

- Empirical model (EIM) [17]

The empirical model elaborated by Paulescu and Schlett [17] had been assessed using the meteorological data recorded by the meteo station of Timişoara.

$$G_g = G_0\left[1 - 0.4645 \cdot e^{-0.69\sin\alpha_s}\right] e^{-\frac{0.05211}{\sin\alpha_s}} \cdot \sin\alpha_s \ [\text{W/m}^2] \tag{11}$$

All the empirical patterns presented above need as inputs just the geographical coordinates of the location chosen and the temporal reference.

Applying the models presented as before in Craiova on 21 June (as a day with high level of irradiation) and on 21 December (as a day with low level of irradiation), respectively, have resulted in the charts presented in Figures 4 and 5.

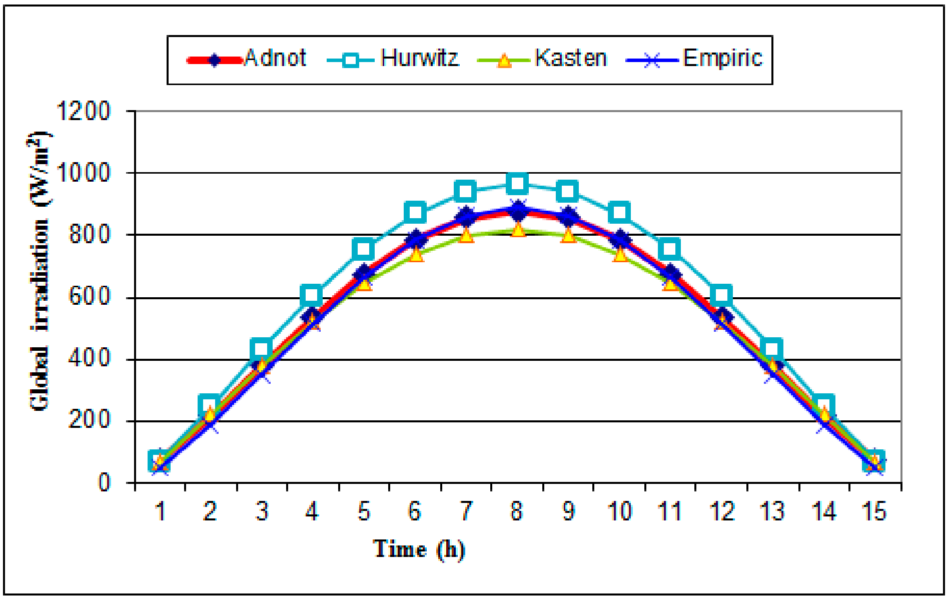


Figure 4. Chart of global solar irradiation, in conditions of a clear sky, on June 21 for the location Craiova.

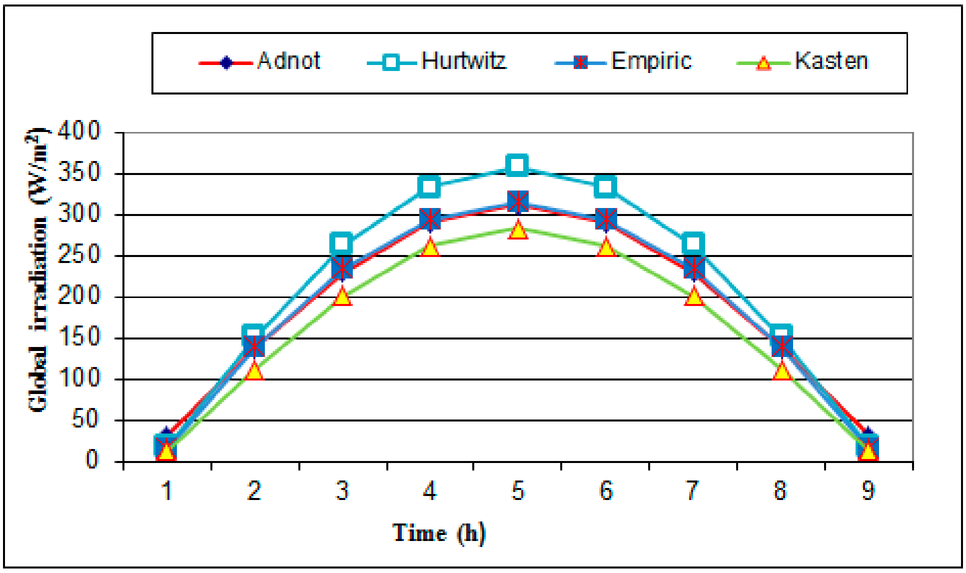


Figure 5. Chart of global solar irradiation, in conditions of a clear sky, on December 21 for the location Craiova.

From the analysis of the charts of solar irradiation in conditions of clear sky in Craiova, we see that the Adnot model and Empirical model are identical for both cases and represent an average of the charts corresponding to the Haurwitz and Kasten models.

2.3. Solar Irradiation Absorbed by a Photovoltaic Panel without Concentration

Broadly speaking, at the weather stations, the measurements related to solar radiation are performed solely on the horizontal plane. In these conditions, the numerical modeling of the solar irradiation absorbed by the photovoltaic panels inclined at an angle β is a topical issue.

In Figure 6 the photovoltaic panel P directed toward south (γ = 0) is depicted. The surface of the panel is denoted by PV, and is inclined to the horizontal with the angle β.

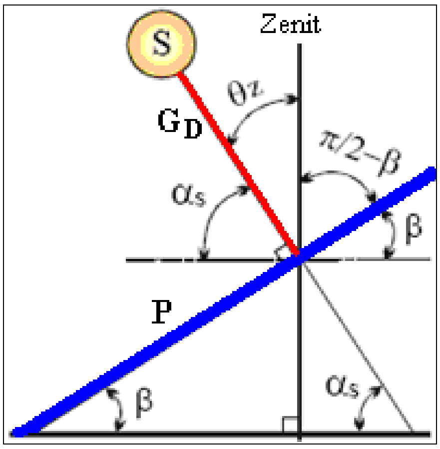


Figure 6. Direct solar irradiation on the PV panel plane at the noon time: ω = 0; γ = 0.

From Figure 6 we see that $\theta_z = \beta$, and from the relationship (4) we obtain:

$$\cos\theta_z = \sin\delta\sin\varphi + \cos\delta\cos\varphi = \cos(\varphi - \delta) \quad (12)$$

Further, one could determine the value of elevation angle of the PV panel:

$$\beta = \phi - \delta \quad (13)$$

In Figure 7 the direct solar radiation is depicted, G_D, on the horizontal plane (a), and $G_{D\beta}$, on a plane inclined to the horizontal with the angle β, (b) according to [14].

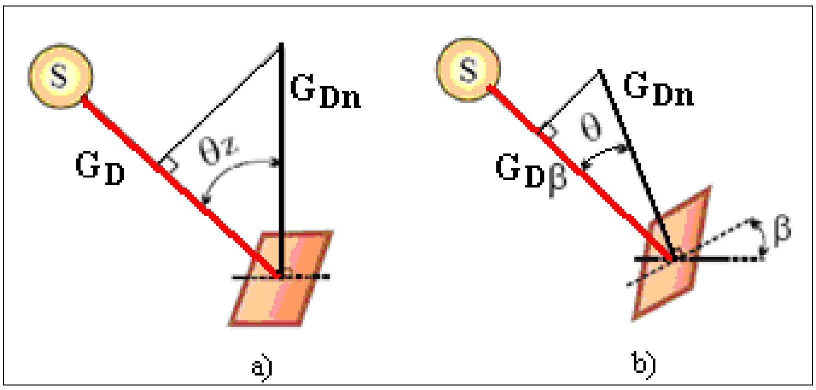


Figure 7. Direct solar irradiation on a horizontal plane (**a**); and on an inclined plane (**b**).

Further, the normal radiation on the photovoltaic panel plane is denoted by G_{Dn}, in order to determine the ratio between G_D and $G_{D\beta}$. Hence, the ratio between the direct radiation on an inclined plane and on a horizontal plane is denoted by $R_G = G_{D\beta} / G_D$.

From Figure 7 it results:

$$G_D = G_{Dn} \cos\theta_z \quad (14)$$

$$G_{D\beta} = G_{Dn} \cos\theta \quad (15)$$

And the ratio R_G:

$$R_G = \frac{G_{Dn} \cos\theta_z}{G_{Dn} \cos\theta} = \frac{\cos\theta_z}{\cos\theta} \quad (16)$$

where θ is the angle of incidence of the solar ray—meaning the angle between the perpendicular on the plane taken into study and the direction of solar ray. For the horizontal plane, one could highlight that $\theta_z = \theta$ (see Figure 7a).

For a plane arbitrary situated the functions cosθ and cosθz are expressed by function combinations of the angles δ, φ, β, γ and ω [16].

It results:

$$\cos\theta_z = \cos\varphi \cos\delta \cos\omega + \sin\varphi \sin\delta \quad (17)$$

For most cases the photovoltaic panel is installed with the active face towards south and γ = 0 for the north hemisphere, or 180°—for the south hemisphere. Substituting the relationship (17) in expression (15) one could obtain the relation below:

$$R_G = \frac{\cos(\varphi - \beta)\cos\delta \cos\omega + \sin(\varphi - \beta)\sin\delta}{\cos\varphi \cos\delta \cos\omega + \sin\varphi \sin\delta} \quad (18)$$

With the calculated value of the ratio RG it will be determined the direct component of the solar radiation on the panel plane PV:

$$G_{D\beta} = R_G \cdot G_D \quad (19)$$

The other two components of solar irradiation—diffuse and reflected are established from the isotropic model of sky roof proposed by Liu and Jordan in 1960 and modified by Klein in 1977 [17].

The diffuse radiation on the inclined plane of the panel, $G_{dif\beta}$ will be calculated with the formula:

$$G_{dif\beta} = \frac{1}{2}(1 + \cos\beta)G_D \quad (20)$$

where G_D is the direct radiation on a horizontal plane calculated on basis of one of the previous patterns.

The reflected radiation on the inclined plane will be calculated with the relationship below:

$$G_{R\beta} = \frac{1}{2}(1 - \cos\beta)\rho G_g \quad (21)$$

where:

ρ is the reflection coefficient of the Earth surface; and

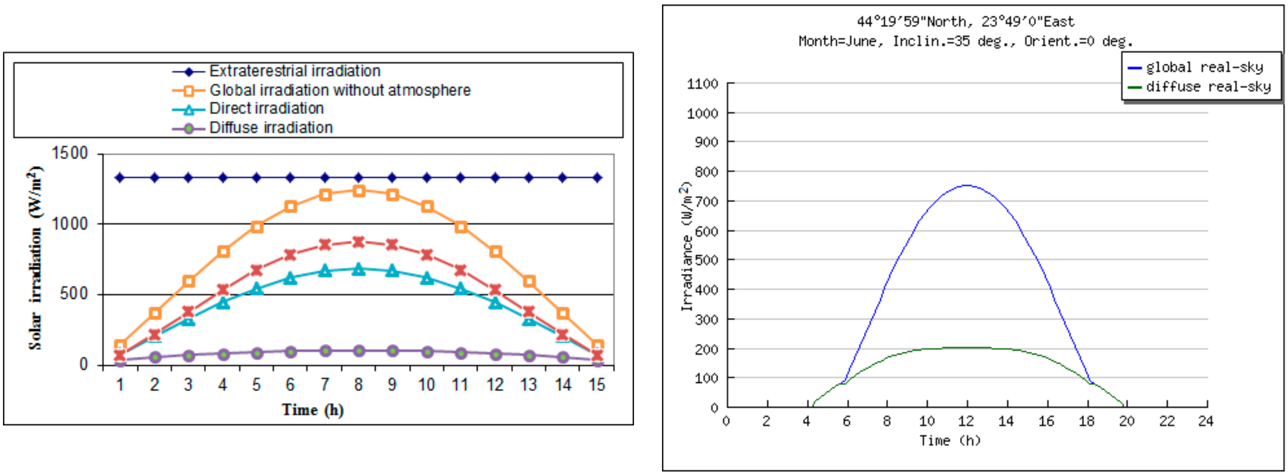
Gg is the global radiation on a horizontal surface.

Consequently, the global radiation on the inclined plane of the PV panel is equal to the sum of three components: direct, diffuse and reflected on the same plane [17]:

$$G_{g\beta} = R_G G_D + \frac{1}{2}(1+\cos\beta)G_D + \frac{1}{2}(1-\cos\beta)\rho G_g \quad (22)$$

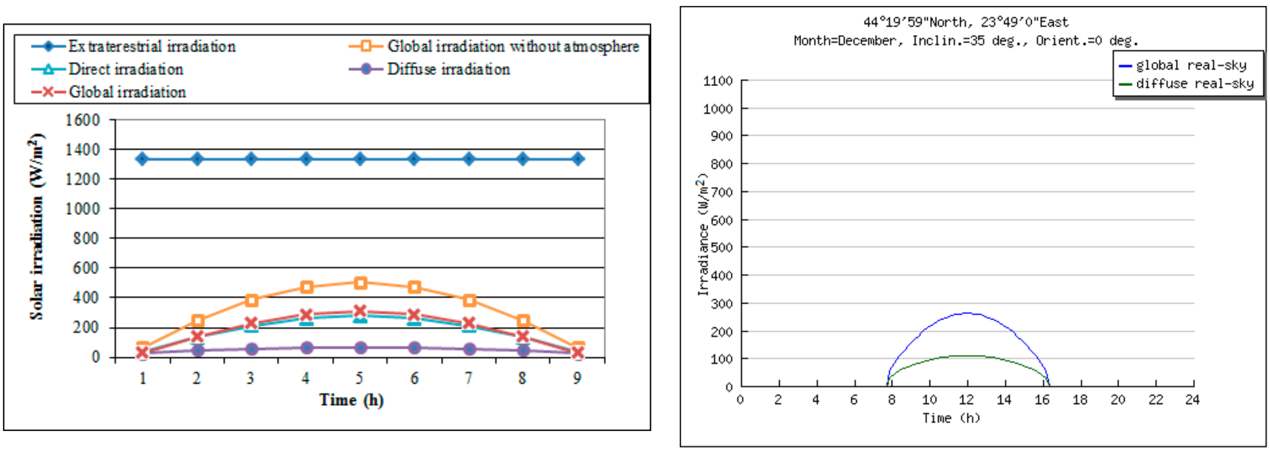
Taking into consideration the presented model, the components of solar radiation absorbed by a photovoltaic panel arbitrary oriented (β = 35°) and disposed in Craiova location have been calculated.

Hence, in Figure 8 solar radiation components calculated with the Adnot model are represented for 21 June, and in Figure 9 the same components for December 21.



(**a**) (**b**)

Figure 8. Solar irradiation absorbed by a PV panel located in Craiova city on 21 June nm (**a**) simulation graphs' results; (**b**) literature graphs according to [18].



(**a**) (**b**)

Figure 9. Solar irradiation absorbed by a PV panel located in Craiova city on December 21 (**a**) simulation graphs' results; (**b**) literature graphs according to [18].

The analysis of the charts following the models' simulation for a comparison with the irradiation values indicated on the maps pointed out by the European Union [18] for Romania emphasized that in Craiova there are no major differences obtained, implying the assertion of the correctness of the adopted models in order to estimate solar irradiation.

Subsequently, a comparative analysis of the solar irradiation values for the situations presented as before is imposed. For this purpose, we calculated the relative and average errors, respectively. The results are presented in Table 1.

Table 1. Calculation of the solar irradiation errors for the adopted Adnot model.

Hour	June				December			
	$G_{g\beta}$ Calculation (W/m²)	$G_{g\beta}$ Literature (W/m²)	Relative Error (%)	Medium Error (%)	$G_{g\beta}$ Calculation (W/m²)	$G_{g\beta}$ Literature (W/m²)	Relative Error (%)	Medium Error (%)
5	0	0	0	3.84	0	0	0	3.16
6	73.5	100	−26.5		0	0	0	
7	218.2	250	−12.72		0	0	0	
8	377.5	400	−5.625		40.5	55	−26.3636	
9	535	540	−0.92593		138	158	−12.6582	
10	675	660	2.272727		230	220	4.545455	
11	785.5	730	7.60274		290	260	11.53846	
12	856	750	14.13333		311	280	11.07143	
13	785.5	730	7.60274		290	260	11.53846	
14	675	660	2.272727		230	220	4.545455	
15	535	540	−0.92593		138	158	−12.6582	
16	377.5	400	−5.625		40.5	55	−26.3636	
17	218.2	250	−12.72		0	0	0	
18	73.5	100	−26.5		0	0	0	
19	0	0	0		0	0	0	

The data presented in Table 1 emphasize that even the relative errors have large values, the average errors are under 5%.

One could note that in the literature, some studies emphasize that the Adnot model has been applied and verified by numerical simulation and direct measurements in the Romanian climate [5,9,13,19].

The literature values were obtained from the database SAF PVGIS Climate [18]. These data are based on calculations from satellite images performed by CM-SAF (Geostationnary MeteoSat and Polar EUMetSat). The database represents a total of 12 years of data. From the first generation of Meteosat satellites (Meteosat 5–7), known as MFG, there are data from 1998 to 2005 and from the second-generation Meteosat satellites (known as MSG) there are data from June 2006 to May 2010. The spatial resolution is 1.5 arc-minutes (about 3 km right below the satellite at 0°N, 0°W). The coverage extends from 0°N (equator) to 58°N and from 15°W to 35°E.

3. Mathematical Model of Solar Irradiation Absorbed by Photovoltaic Panel with Low Concentration

In order to estimate the solar irradiation absorbed by PV panel, it is necessary to describe the geometrical model of the low radiation concentration system [6,8,20,21]. In order to determine the most adequate shape for the low concentrator system, geometric modeling was conducted in [20].

The low radiation concentration system (LCPV) consists in two vertical mirrors disposed symmetrically in the lateral extremities of the PV panel. This system is similar to the system "WS Heliots with DoubleSun" [22] (see Figure 10).

Figure 10. WS Heliots system, with DoubleSun technology, according to [22].

The geometrical model of the concentration system is depicted in Figure 11. The solar rays reflected by each mirror cover a half of the panel surface. Thus, the two lateral mirrors reflect the solar light on the entire surface of the PV panel.

In order to describe the geometry of the considered LCPV system there have been denoted the following quantities (see Figure 11) [20,21]:

- x is the angle between the mirror and the photovoltaic module, and is a constant parameter;
- h is the maximum incidence angle created by the solar ray with the normal to the photovoltaic arrays;
- k represents the ratio between the mirrors width (Lm) and the photovoltaic module width (Lp);
- c_1, c_2 are the width coefficients of PV module brushed by the rays reflected by the mirror;
- k_l is the longitudinal deviation coefficient, defined as the ratio between the additional length of the mirror (necessary for the compensation of the deviation of solar rays reflected, caused by the elevation deviations of the PV module from the solar elevation) and the photovoltaic module width.

The global radiation received normally by the inclined plane provided with concentrator elements type lateral mirrors is described by the relation [6]:

$$G_{g\beta_{conc}} = G_{g\beta} + \sum G_{M_{1,2}} \tag{23}$$

where $G_{M1,2}$ is the irradiation reflected by the two mirrors

$$G_{M_{1,2}} = G_D \cdot \cos\left(h_{R_{1,2}}\right) \tag{24}$$

where $h_{R1,2}$ is the incidence angle formed between the ray reflected by each mirror and the normal to the photovoltaic panel.

The other components of the solar irradiation on the PV panel plane are presented above.

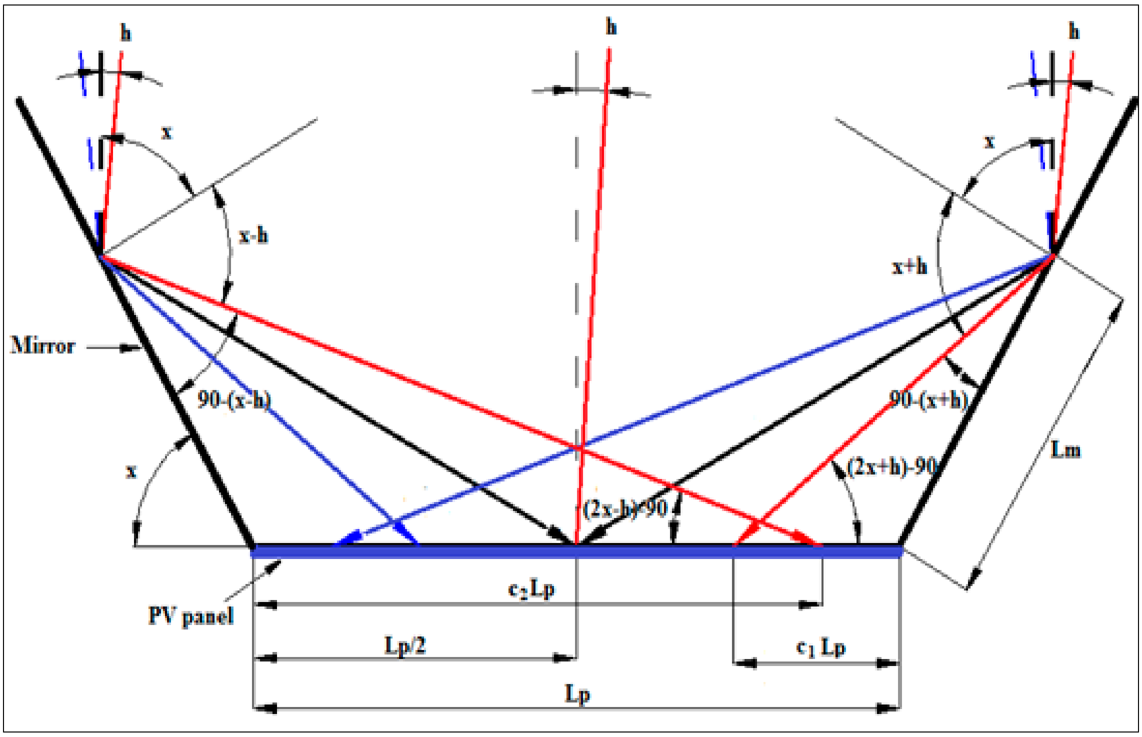


Figure 11. Geometric model of LCPV system, according to [20,21].

Accordingly, the graphical evolution of the solar irradiation absorbed by the PV panel with a concentration system, for the same conditions as before, are depicted in Figures 12 and 13.

The geometrical parameters that had been taken into consideration for simulation are presented below: $\beta = 35°$; $x = 55°$, $60°$, and $65°$; $h = 7.5°$; $k = 0.6, 1, 1.5$; $c_1 = c_2 = 1.35$; $k_l = 0.2$.

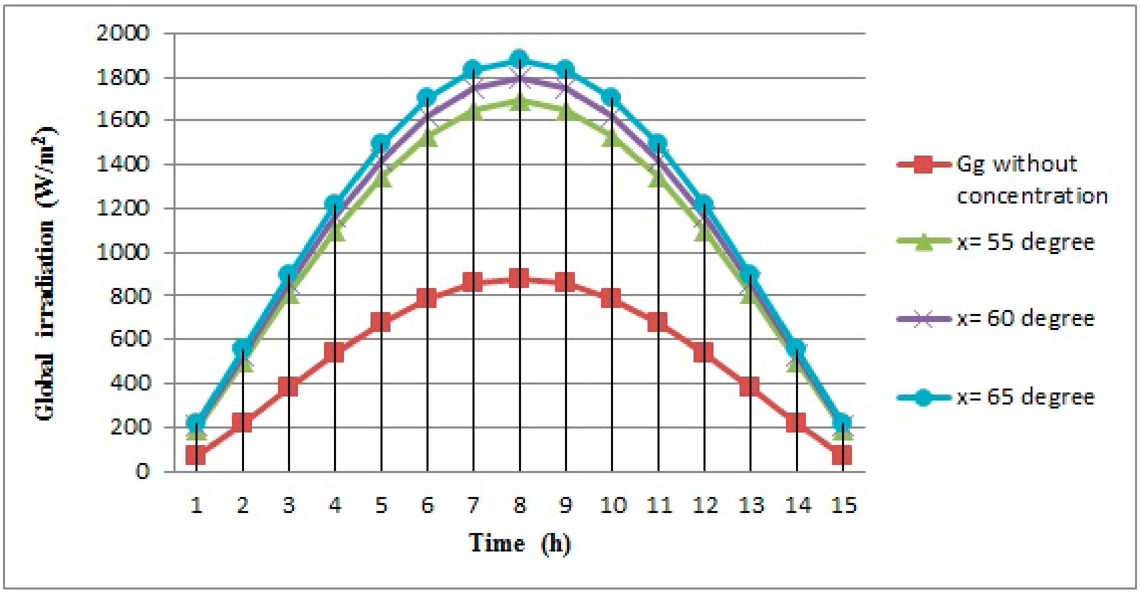


Figure 12. Total irradiation absorbed by the PV panel with concentration system on 21 June.

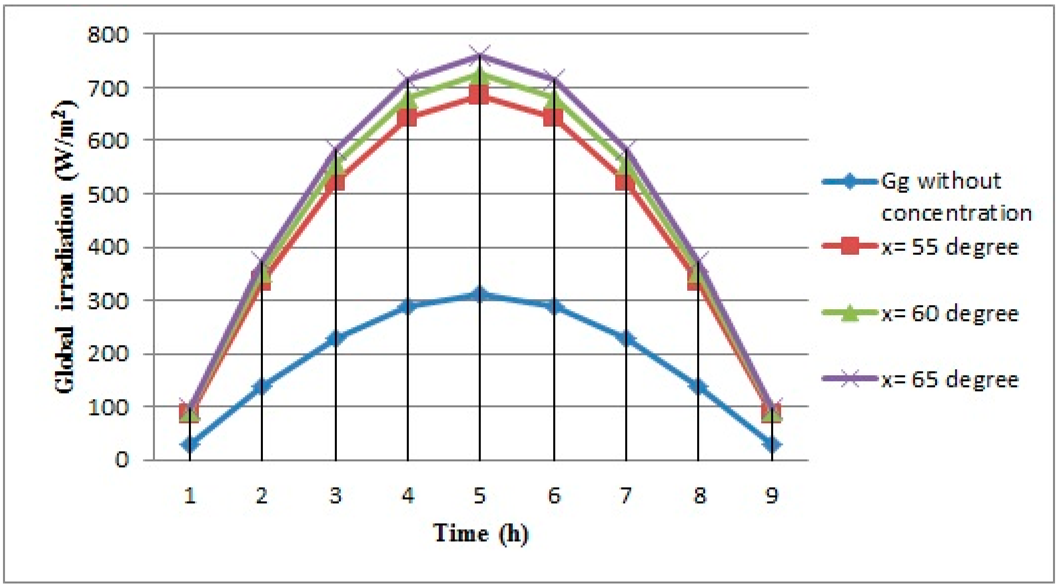


Figure 13. Total irradiation absorbed by the PV panel with concentration system on 21 December.

In the framework of performed simulations, mathematical models for a certain location for the days with extreme values of the solar irradiations (21 June and 21 December, respectively) have been particularized, since this way, one could easily verify the correctness of the patterns presented.

The charts emphasize that the tilt angle of mirrors (x) has a significant influence on solar irradiation. For the performed simulation, the optimum values of the angle have been considered, up to 65°. One might note that values over 65° could lead to shading of the PV panel [23].

The solar radiation absorbed by a LCPV panel depends on the geometric parameters, tracking system accuracy, different tracking programs and tracker types (equatorial, azimuth or pseudo-equatorial) [6,20,23]. In this paper, we used the pseudo-equatorial tracking system.

4. Experimental Results

The purpose of the experimental determinations is to visualize the distinct measured values of the solar irradiation on the plane of the photovoltaic panel without concentration and with low concentration, respectively. The structure of the experimental equipment for the measurement of solar irradiation is depicted in Figure 14.

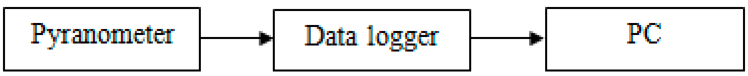


Figure 14. Structure of experimental equipment.

The experimental determinations have been carried out under the laboratory conditions, because of the lack of two pyranometers, in order to measure simultaneously the solar irradiation for the two cases analyzed in this study.

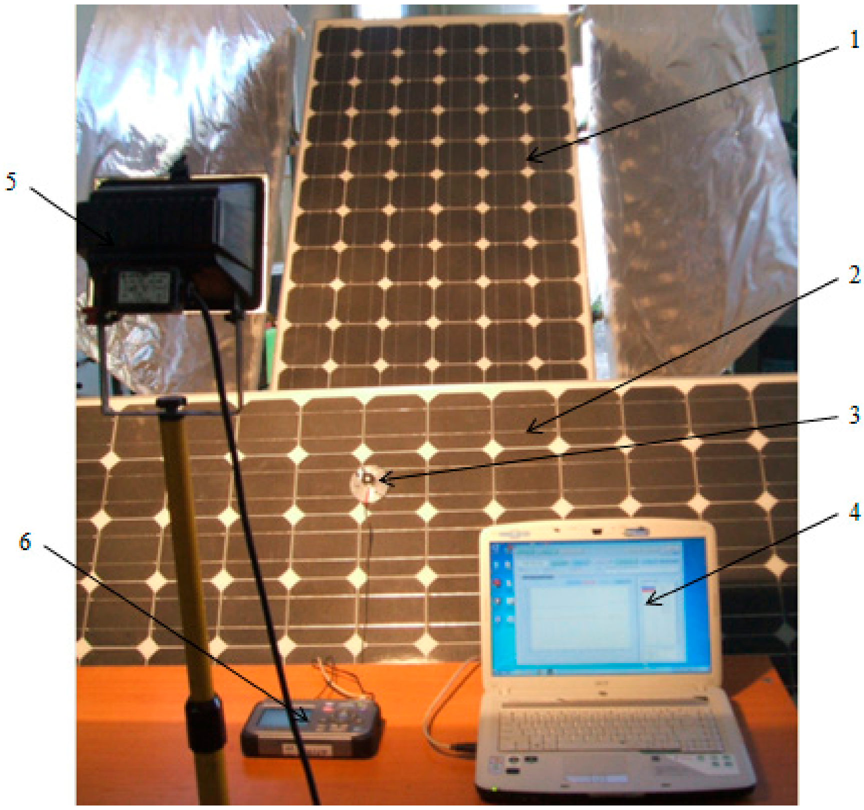


Figure 15. Experimental equipment: (1) LCPV panel; (2) PV panel without concentration, (3) pyranometer; (4) PC; (5) solar lamp; (6) data logger.

Consequently, a solar lamp to ensure identical lighting conditions in the two analyzed situations has been used, as well as a single pyranometer to measure successively the solar irradiation values. The used pyranometer to measure the global solar irradiation was Li-200S, manufactured by Li-Cor Inc. (Lincoln, NE, USA) with a measurement error ±5%, and with a measurement accuracy comparable to pyranometers of class 1, according to [24]. This pyranometer transmits a current output signal with a sensitivity of 10 μA at 1000 W/m^2.

In order to convert the output signal into a voltage signal (mV) which is necessary for Data logger, a resistor of 100 Ω has been used, resulting in a sensitivity of 1 mV at 1000 W/m^2.

The experimental results are depicted in Figures 16 and 17.

The geometrical parameters of the experimental system have the following values: $\beta = 35°$; $x = 55°$ and 65°; $h = 7.5°$; $k = 1$; $c_1 = c_2 = 1.35$; $k_l = 0.2$.

As shown in the experimental charts, the global irradiation measured on the plane of the photovoltaic panel without concentration (see Figure 16) has values roughly of 600 W/m^2, while that measured on the plane of the photovoltaic panel with low concentration for mirrors tilt $x = 55°$ (see Figure 17) has values roughly of 1280 W/m^2. For the mirrors' tilt at $x = 65°$ the solar irradiation has the value 1400 W/m^2 (see Figure 18).

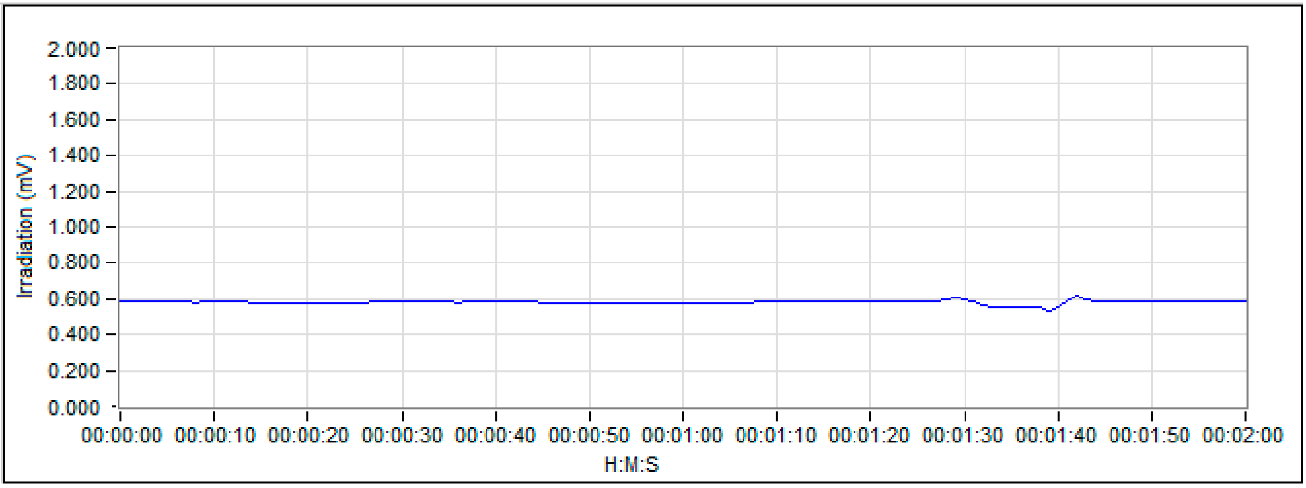


Figure 16. Chart of solar irradiation measured on the plane of the photovoltaic panel without concentration.

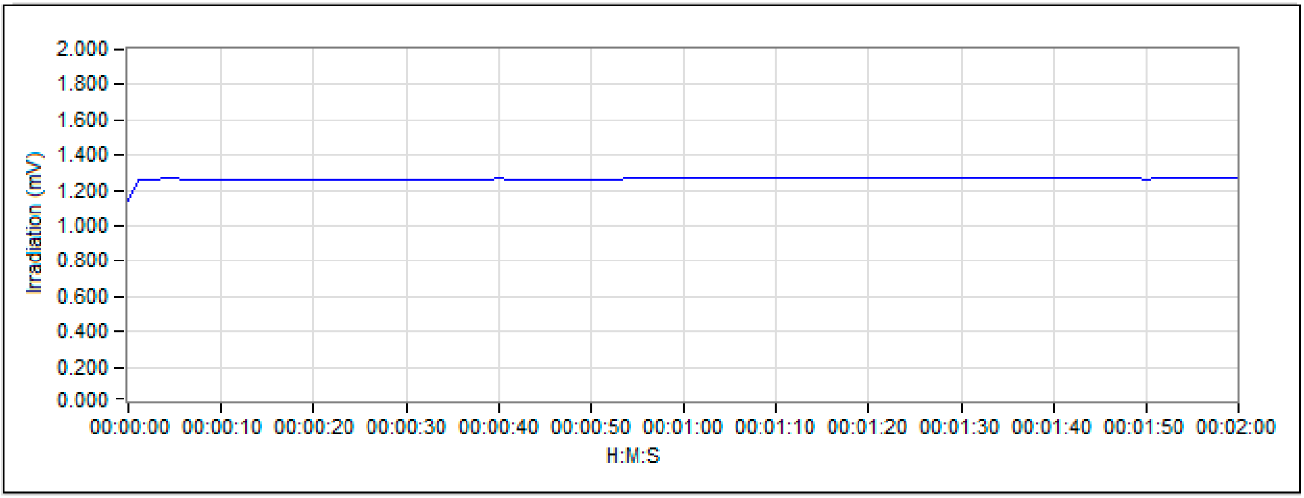


Figure 17. Chart of solar irradiation measured on the plane of the photovoltaic panel with low concentration for mirrors tilt x = 55°.

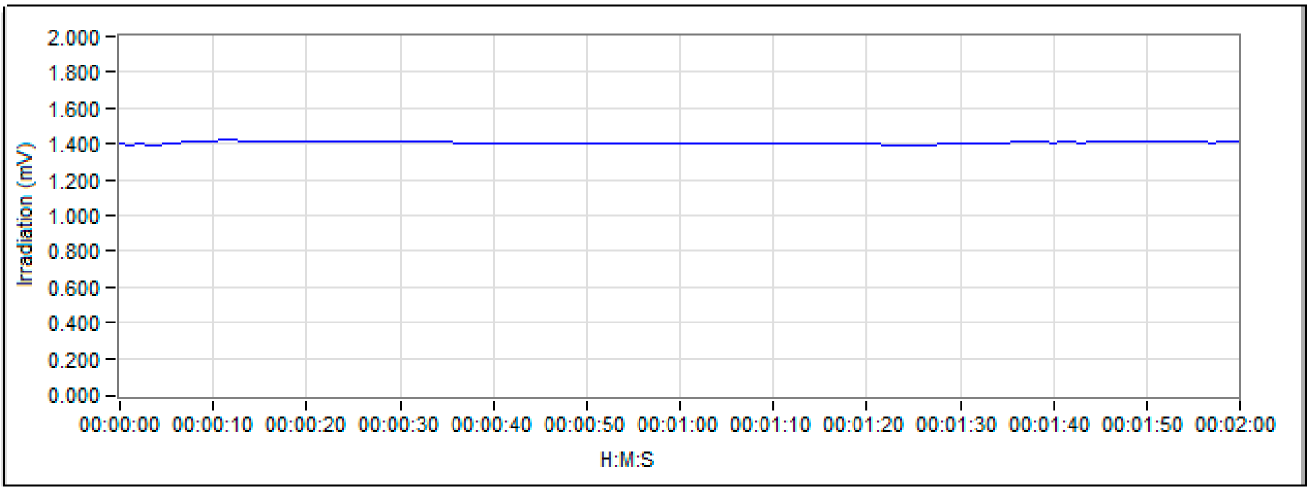


Figure 18. Chart of solar irradiation measured on the plane of the photovoltaic panel with low concentration for mirrors tilt x = 65°.

5. Conclusions

This paper presents some of the existing models in the literature in order to address meaningfully solar irradiation assessment. These patterns have been particularized for the conditions specified for a certain location, namely Craiova, Romania.

Validation of these models was performed by numerical simulation.

Correspondingly, from the charts following the simulations one could highlight several conclusions:

- the models Adnot and Empiric for the global irradiation assessment can be adapted in the best way for the conditions of the location chosen for this study;
- the main advantage of these models is their simplicity (these models have as input parameters only the location and time marks), which makes them easy to use in practice;
- the values of solar irradiations obtained through the simulations are close enough to those indicated on the maps elaborated by professional institutes for the site took into study;
- during travel through the atmosphere the solar rays decrease intensity as they are approaching the Earth;
- the values of the solar irradiation on the PV panel plane are roughly two times higher than those on the PV panel plane without a concentration system.

The simulation results emphasize that the models presented might be utilized for the calculation of solar irradiation specific to the location chosen.

In addition, for the chosen location, estimation of the solar irradiation absorbed by the photovoltaic panels with and without concentration has been realized through experiments. The experimental results highlight differences, which twice the size between the values of solar irradiation measured on the plane of photovoltaic panel, with concentration than the values measured on the plane of photovoltaic panel without concentration.

Acknowledgments

This work was partially supported by the grant number 29C/2014, awarded in the internal grant competition of the University of Craiova.

Author Contributions

Publications of literature provide information regarding the mathematical models to calculate the solar irradiation. In this study, the authors have particularized several empirical models for the location Craiova, Romania.

This study encompasses also an estimation method of the solar irradiation available on the plane of photovoltaic panels with and without concentration of the solar radiation. The method has been verified through numerical and experimental simulation.

Ionel L. Alboteanu designed the research and particularized the mathematical models of the solar irradiation. He also performed the experimental tests and wrote the paper. Cornelia A. Bulucea carried out the analysis of data and conducted the research. Sonia Degeratu participated in the mathematical models' analysis. All authors read and approved the final manuscript

Conflicts of Interest

The authors declare no conflict of interest.

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