Determining the solar radiation absorbed by the photovoltaic panels located in Craiova city, Romania, in order to estimate an optimal energy production

Ionel L. Alboteanu, Cornelia A. Bulucea, Carmen A. Bulucea, Sonia Degeratu

***Abstract*—**The energy production of a photovoltaic system is mainly depending on the solar irradiation, (in W/m^2), available in the location where it is placed. Based on the solar radiation value, (in Wh/m^2) the photovoltaic system can be dimensioned, and estimates can be made of the generated electrical energy. This paper presents aspects regarding the evaluation of solar potential and energy production of photovoltaic systems in Craiova city, Romania. For the chosen location, the solar radiation was calculated for a horizontal surface, respectively, on the inclined plane of a photovoltaic panel for different angles of inclination. The maximum radiation absorbed by the panel and the optimal angle of inclination of the panel was then determined. Also, solar radiation was measured on the plane of the photovoltaic panel inclined to the optimal angle. Based on the obtained results the energy produced by a photovoltaic system located in that location was estimated.

***Keywords*—**Solar irradiation, photovoltaic panels, photovoltaic system, solar energy. optimum tilt panel.

I. INTRODUCTION

ENERGY is currently a key issue for the global economy. World economic growth is threatened by the harsh reality of the depletion of world reserves of oil, natural gas, coal, nuclear fuel, and unreasonable exploitation of forests that are recovering at a slower rate than grazing.

One of the greatest challenges of the 21st century is to ensure that every citizen of the planet Earth has access to clean (non-polluting) energy, sustainable and at a reasonable cost [1].

In many places on Earth, the Sun has the ability to solve the need for energy that is becoming more and more acute with the increase of the world population and the raising of its standard of living, along with the exhaustion of conventional sources [1].

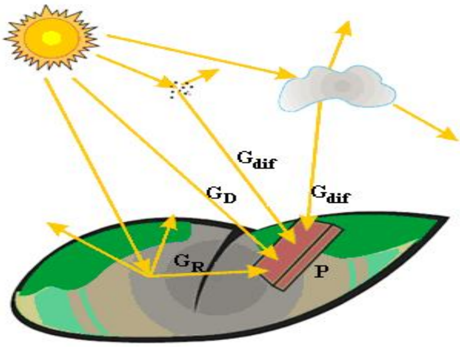

Fig. 1. Components of solar irradiation according to [2].

In order to investigate the possibilities of using the solar radiant energy (irradiation), it is useful to know the global radiation values received by the surface unit during a day, a month or a season in different geographic areas.

On the other hand, this movement is not the same every day, because the Earth revolution around the Sun. Even the use of a plane captor that is usually fixed, it is useful to know the movement to evaluate the captor optimal inclination through the horizontal position.

Because the nocturnal Sun movement, the solar sunray are captained by Earth for different angles, changing from area to area, hour to hour, from season to season.

Of the meteorological factors, a particular influence on the solar radiation on the ground has: the transparency of the atmosphere, the nebulosity, the type of clouds, as well as their thickness and position [2]. This is how we can talk about (Fig. 1):

- Direct irradiation (G_D), is the radiation received from the Sun without being scattered by the atmosphere.

- Diffuse irradiation (G_{dif}), that occurs when the solar ray

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passing through the atmosphere is scattered, in other words, diffused in all directions.

- Albedo or reflected irradiation (GR), is the radiation reflected from the surface of the earth and which falls on the solar panel.

- Total or global solar irradiation (G) is the sum of the three components falling on any surface.

Usually, in the calculations and in the publications of the specialized institutes, the global radiation is considered.

In this paper we present the theoretical methods for the calculation of the solar irradiation available in Craiova city, Romania, completed with the real values obtained from the measurements.

II. SOLAR RADIATION CALCULATION

A. *Solar radiation on a horizontal surface*

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 [3], 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, that models the global solar irradiation under conditions of a clear sky, by using the relationship [4]:

$$G_g = 951.39(\sin\alpha_s)^{1.15} \quad [\text{W/m}^2] \qquad (1)$$

where:

- is sun elevation angle

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 [4].

- Haurwitz model [4].

$$G_g = 1098\cdot e^{\frac{0.057}{\sin\alpha_s}}\cdot\sin\alpha_s \; [\text{W/m}^2] \qquad (2)$$

- Kasten model [5]

$$G_g = 910\cdot\sin\alpha_s - 30 \; [\text{W/m}^2] \qquad (3)$$

- Empirical model -EIM [6]

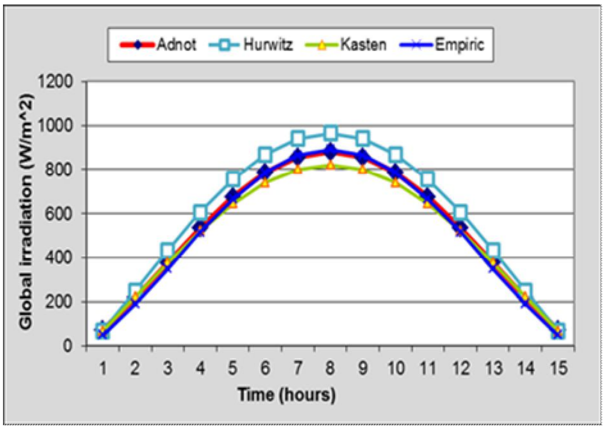

Fig. 2. Chart of global solar irradiation, in conditions of a clear sky, on June 21 for Craiova

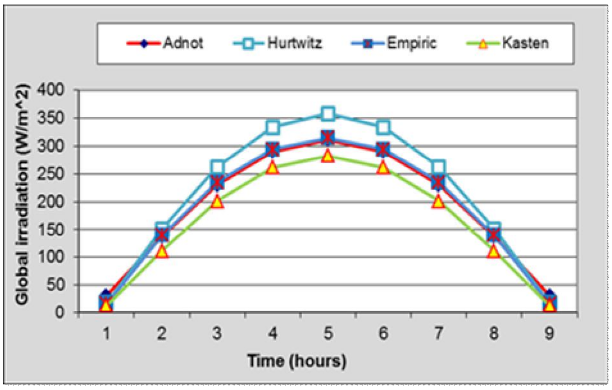

Fig. 3. Chart of global solar irradiation, in conditions of a clear sky, on Dec. 21 for Craiova

The empirical model elaborated by Paulescu and Schlett [6] had been assessed using the meteorological data recorded by the meteo station of Timişoara.

$$G_g = G_0\left[1-0.4645\cdot e^{-0.69\sin\alpha_s}\right]e^{-\frac{0.05211}{\sin\alpha_s}}\cdot\sin\alpha_s \; [\text{W/m}^2](4)$$

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

Applying the models presented as before for the location of Craiova City (latitude: φ = 44,23°, longitude λ = 23,87°) on the day of June 21 (as a day with high level of irradiation) and on the day of December 21 (as a day with low level of irradiation), respectively, the charts presents in Figures 2 and 3 have resulted.

From the analysis of the charts of solar irradiation in conditions of clear sky for the location Craiova it results that the Adnot model and Empirical model are identical for both cases and represents an average of the charts corresponding to Haurwitz model and Kasten model.

Using dedicated software BlueSol [7] was obtained monthly average of solar radiation based on NASA-SSE

Craiova
Romania

Source of climatic data: NASA-SSE

Latitude: 44.31 °
Longitude: 23.8 °
Altitude: 105.0 m
T Max: 27.0 °C
T Min: -4.0 °C

Monthly average irradiance on horizontal plane

Month	Global [kWh/m²]	Diffuse [kWh/m²]
January	47.74	19.84
February	66.64	26.32
March	107.26	42.47
April	132.3	57
May	169.26	69.44
June	183	71.1
July	193.13	68.2
August	171.43	57.66
September	120.6	45.3
October	78.74	34.1
November	47.4	22.2
December	38.13	17.67
Year	112.97	44.28

Fig. 4. Monthly average irradiance of Craiova location

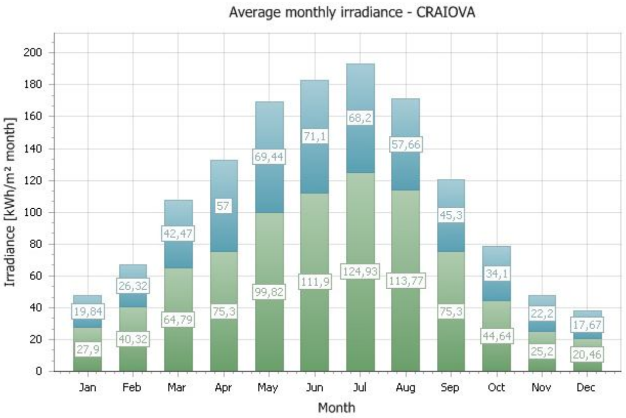

Fig. 5. Chart of monthly average irradiance of Craiova location

database (Fig. 4 and Fig. 5).

The graphs show that the yearly average of global solar irradiation is 112.97 [kWh/m^2] and the monthly average is between 38.13 [kWh/m^2] and 193.13 [kWh/m^2].

B. *Solar radiation on a tilt photovoltaic panel*

The optimum solution could be the pursuance of the Sun in it's apparently movement on the celestial arch, so that the beam falls perpendicularly on the interest surface [8].

Solar systems with flat surfaces are built without pursuance. They are oriented to the south and installed under an optimal angle from the horizon for the specific location and the exploitation period along the year.

The optimum tilt angle is approximated precisely sufficient with the relation:

$$\theta = \varphi - \delta \tag{5}$$

θ - the solar panel bent angle, [°];

φ - the geographical latitude of the location, [°];

δ - the Sun declination calculated with relation 7, [°];

Generally, the tables and graphics regarding solar radiation present values for incident solar radiation through a horizontal surface [9].

To design a solar system, we must know the solar radiation for a horizontal surface, the incident solar radiation through a horizontal surface. The solar radiation G_{D0} received, during one day, by a unit horizontal area outside the Earth's atmosphere is calculated with relation [10], [11], [12]:

$$G_{D0} = \frac{24}{\pi}\cdot E_0 \cdot \left[1+0{,}33\cdot\cos\left(\frac{2\pi\cdot n}{365}\right)\right]\cdot \qquad [\text{Wh/m}^2] \quad (6)$$
$$\cdot\left(\cos\varphi\cdot\cos\delta\cdot\sin\omega_s + \omega_s\cdot\sin\varphi\cdot\sin\delta\right)$$

where:

E_0=1367 W/m^2 – is solar constant;

n – number of the days in the year (for example n=1 for 1 January);

ω- hour angle for the sunrise, [°];

Solar declination for a usually day "n" it can be calculated using an Cooper approximate formula:

$$\delta = 23{,}45\cdot\sin\left(360^\circ\,\frac{284+n}{365}\right)\left[^\circ\right] \tag{7}$$

The sunrise solar hour angle is:

$$\omega_s = \cos^{-1}\left(-\tan\varphi\cdot\tan\delta\right)\left[^\circ\right] \tag{8}$$

The sunset hour angle is:

$$\omega_s = -\cos^{-1}\left(-\tan\varphi\cdot\tan\delta\right)\left[^\circ\right] \tag{9}$$

The clearness index k_T is calculated for each month of the year using the relation [10]:

$$k_T = \frac{G_g}{G_{D0}} \tag{10}$$

Gg- global radiation on a horizontal plane, [Wh/m^2•day].

The clearness index k_T describes the (average) attenuation of solar radiation by atmosphere at a given site during a given month.

Diffuse solar radiation G_{dif} for a horizontal plane is approximated using the equation [10]:

$$\frac{G_{dif}}{G_g} = 1-1{,}13\cdot k_T \Rightarrow \qquad [\text{Wh/m}^2\cdot\text{day}] \quad (11)$$
$$G_{dif} = G_g\cdot\left(1-1{,}13\cdot k_T\right)$$

The direct solar radiation G_D, through a horizontal plane is:

$$G_D = G_g - G_{dif} \qquad [\text{Wh/m}^2\cdot\text{day}] \qquad (12)$$

The direct solar radiation $G_D(\theta)$ on a south-facing panel inclined at an angle θ to the horizontal surface is:

$$G_D(\theta) = G_D \cdot \frac{\cos(\varphi-\theta)\cdot\cos\delta\cdot\sin\omega_0 + \omega_0\cdot\sin(\varphi-\theta)\cdot\sin\delta}{\cos\varphi\cdot\cos\delta\cdot\sin\omega_s + \omega_s\cdot\sin\varphi\cdot\sin\delta}$$
$$+\frac{\omega_0\cdot\sin(\varphi-\theta)\cdot\sin\delta}{\cos\varphi\cdot\cos\delta\cdot\sin\omega_s + \omega_s\cdot\sin\varphi\cdot\sin\delta} \ [\text{Wh/m}^2\cdot\text{day}](13$$

where:

$$\omega_0 = \min\{\omega_s, \omega_s'\} \qquad (14)$$

ωs - is the sunrise angle above the horizon, given by the relation (8)

$$\omega_s' = \cos^{-1}[-\tan(\varphi-\theta)\cdot\tan\delta]\,[^\circ] \qquad (15)$$

ω’s - is the sunrise angle above a plane inclined at angle θ to the orizontal.

Assuming that the diffuse radiation is distributed isotropically over the sky dome, the diffuse solar radiation on the inclined surface is given by:

$$G_{dif}(\theta) = \frac{1}{2}\cdot(1+\cos\theta_{\hat{i}ncl})\cdot G_{dif} \quad [\text{Wh/m}^2\cdot\text{day}] \qquad (16)$$

The reflected solar radiation is generally small, and a simple isotropic model is usually sufficient, thus can be determined with the relation:

$$G_R(\theta) = \frac{1}{2}\cdot(1-\cos\theta)\cdot\rho\cdot G_g \quad [\text{Wh/m}^2\cdot\text{day}] \qquad (17)$$

ρ - reflectivity of the surrounding area.

Table I. Typical reflectivity values for some ground covers [13]

Ground cover	**Reflectivity, ρ**
dry bare ground	0,2
dry grassland	0,3
desert sand	0,4
snow	0,5÷0,8

In this case we can evaluate the global radiation Gg(θ) on an tilt surface as sum of direct radiation, reflected and diffuse:

$$G_g(\theta) = G_D(\theta) + G_{dif}(\theta) + G_R(\theta) \ [\text{Wh/m}^2\cdot\text{day}] \qquad (18)$$

The global solar radiation (irradiance) on an inclined surface for January is calculated knowing the irradiance for a horizontal surface (Fig. 4).

In Table 2 are presented the values of the solar radiation obtained for different angles of inclination of the photovoltaic panel.

Table 2. Calculated of solar radiation for a tilt surface

Month	**Gg [kWh/m²·day]**	**k$_T$**	**The global solar radiation for a inclined surface - Gg(θ) [kWh/m²·day]**									
			0°	**10°**	**20°**	**30°**	**40°**	**50°**	**60°**	**70°**	**80°**	**90°**
Jan.	4,46	0,322	1,440	1,682	1,895	2,070	2,204	2,290	2,327	2,314	2,251	2,140
Feb.	6,029	0,373	2,250	2,523	2,750	2,924	3,039	3,092	3,080	3,005	2,869	2,676
Mar.	7,638	0,447	3,420	3,721	3,951	4,102	4,169	4,151	4,049	3,864	3,603	3,274
Apr.	8,627	0,530	4,580	4,790	4,910	4,932	4,856	4,683	4,420	4,073	3,656	3,180
May	8,643	0,645	5,580	5,655	5,631	5,501	5,267	4,934	4,512	4,016	3,464	2,880
June	8,265	0,748	6,190	6,164	6,037	5,802	5,458	5,016	4,487	3,891	3,252	2,606
Julie	7,198	0,824	6,530	6,568	6,488	6,278	5,940	5,482	4,918	4,267	3,556	2,821
Aug.	7,767	0,719	5,590	5,287	5,942	5,929	5,786	5,517	5,129	4,637	4,055	3,407
Sep.	7,225	0,561	4,060	4,403	4,654	4,805	4,851	4,791	4,627	4,363	4,007	3,571
Oct.	6,017	0,447	2,690	3,039	3,329	3,550	3,696	3,762	3,747	3,649	3,473	3,225
Nov.	4,626	0,371	1,720	2,021	2,284	2,500	2,663	2,768	2,813	2,795	2,714	2,575
Dec.	3,933	0,310	1,220	1,444	1,641	1,807	1,934	2,021	2,064	2,061	2,014	1,924
Mean annual			**3,773**	**3,941**	**4,126**	**4,183**	**4,155**	**4,042**	**3,848**	**3,578**	**3,243**	**2,857**

Using the value from the Table 2 we can represent the average solar radiation graphic for the warmest month of the year (July), for the coldest month of the year and the yearly average for Craiova (Fig. 6).

Also was illustrating the graphical of the year daily radiation for Craiova corresponding to the tilt angle of the PV panel (Fig. 7). The charts correspond to the tilt angles of 20^o, 40^o and 60^o respectively.

In order to estimate the maximum of solar energy captured by the PV panel, the optimal monthly and yearly angles of inclination, was calculated. The resulting graphs are shown in Figure 8.

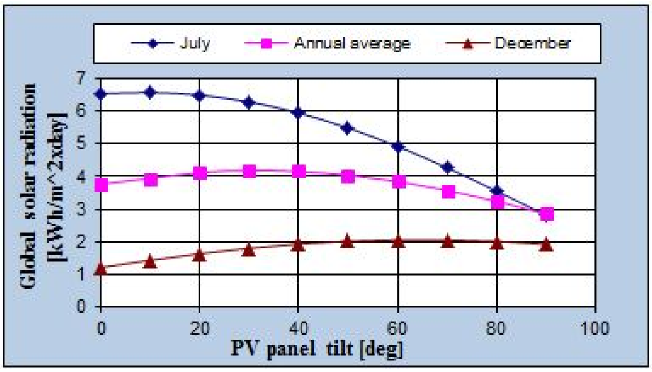

Fig. 6. Solar radiation for different period of the years on a tilt photovoltaic panel

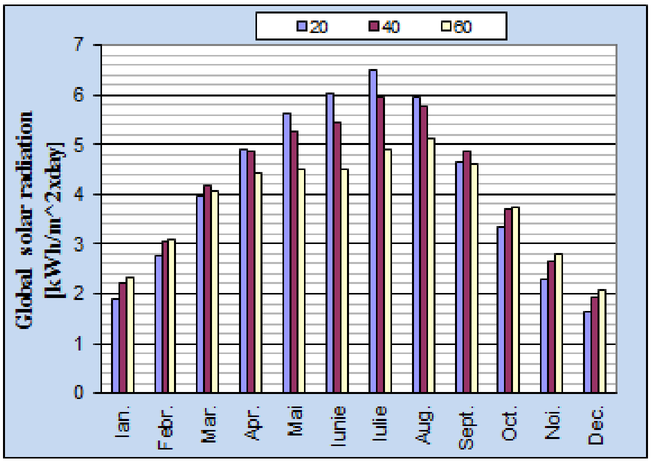

Fig. 7. Daily radiation for Craiova over the year for selected angles of PV panel inclination

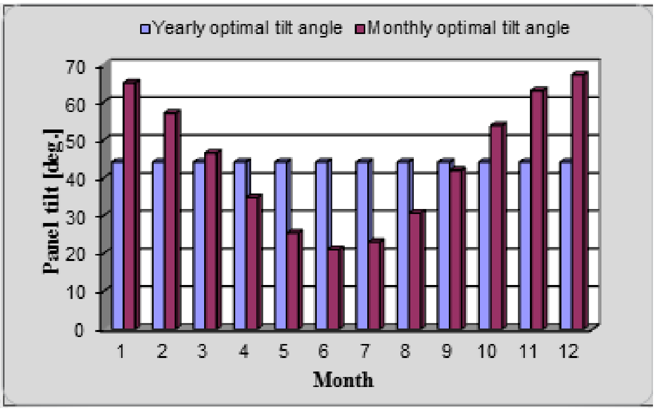

Fig. 8. Optimally tilt angle of PV panel for Craiova City

Following calculations result that the solar radiation captured by PV panel for monthly optimal angles increasing with 1, 44% versus a solar radiation absorbed for yearly optimal angle.

III. SOLAR RADIATION MEASURED

Measurement of solar irradiation was carried out with the monitoring equipment of a photovoltaic system located in Craiova (Fig. 9 and Fig. 10).

Weather parameters were monitored online and stored on an SD card.

Data is downloaded in * CSV format that can be easily imported into Excel and then processed in the desired form.

To analyze the correctness of calculated values of irradiation (Fig. 2 and Fig. 3) in Fig. 11 and Fig. 12 there are depicted the graphs resulting from the recordings made with the monitoring system.

Fig. 9. Equipment for measuring weather parameters: 1- pyranometer; 2- anemometer.

SENS0802:38491		
Radiation	898	W/m^2
Module temperature	37.3	°C
Ambient temperature	27.6	°C
Wind speed	3.1	m/s
Radiation (external)	0	W/m^2

Fig. 10. Window of monitoring system

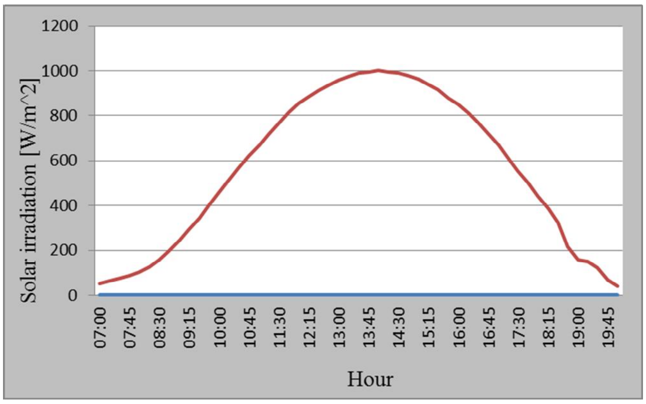

Fig. 11. Chart of global solar irradiation, measured on PV panel plane in 2016.06.21 for Craiova location

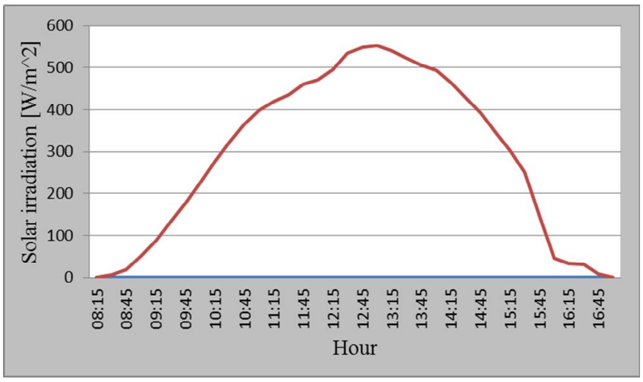

Fig. 12. Chart of global solar irradiation, measured on PV panel plane in 2016.12.21 for Craiova location

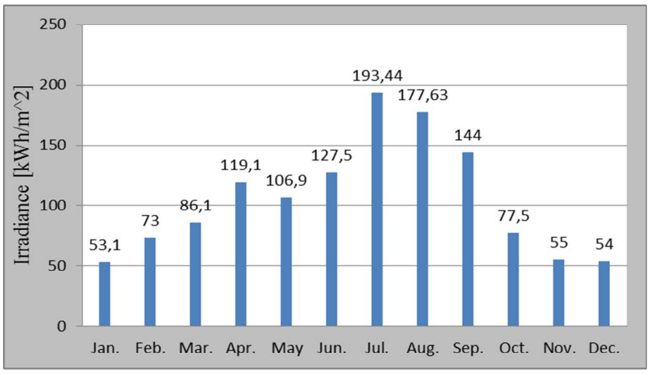

Fig. 13. Chart of monthly average irradiance measured on PV panel plane for Craiova location

Also, for a comparison of monthly average irradiation obtained with BlueSol software (Fig. 5), in Fig. 13 the chart of the average monthly solar radiation obtained from the measurements.

As can be seen in Fig. 11 and Fig. 12 the measured solar irradiation values are higher than the calculated irradiation values because they were measured on the plane of the PV panels inclined at an angle of 45°. The calculated values were calculated for a horizontal plane.

IV. EVALUATE OF ENERGY PRODUCTION OF A PV SYSTEM LOCATED IN CRAIOVA

The photovoltaic system having a nominal power of 3 kW, located in Craiova and connected to the electrical distribution grid in Low voltage Single-phase alternating current a 230V have been experimented (Figure 14).

Using the BlueSol software, based on the available solar irradiation values at the Craiova location and the catalog data of the PV system equipment, the electric energy output of the analyzed system was estimated (Figure 15).

PV panels are made of Conergy 245 PJ polycrystalline silicon, with an efficiency of 15.4%. Also total system losses are about 14%.

Fig. 14. Photovoltaic system analyzed, located in Craiova

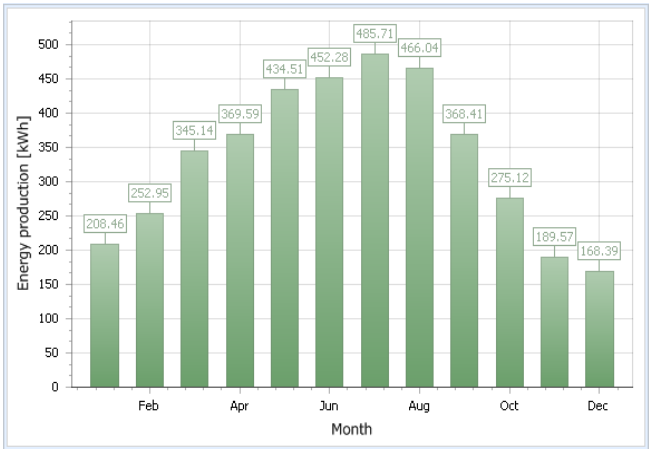

Fig. 15. Monthly energy production of PV system expected during the year

Summing up the monthly energy output results in an annual PV system energy output of about 4020 [kWh].

V. CONCLUSION

In this study was determined the solar irradiation by calculation and measurements, for a certain location. One could note that the measured values were close to the calculated values.

The yearly optimal tilt angle for the PV panels located in Craiova is 45°. For this tilt angle, solar radiation has been calculated and measured.

The average yearly radiation determined with the BlueSol software is 112.97 [kWh/m^2], and the one obtained by the measurements is 105,6 [kWh/m^2].

It must be highlighted that based on the information obtained on the solar irradiation available at that location, it is possible to estimate the optimum energy output of the PV system.

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