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COMPARISON BETWEEN MEASUREMENTS AND MELISS SIMULATIONS OF THE DIRECT SOLAR IRRADIANCE FOR A WINTER MONTH IN BRASOV

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Abstract
When aiming to increase the solar share in the energy demand of a building in the cold season, one solution is to increase the surface of solar thermal collectors but this could negatively affect the system during summer by overheating. Thus, an accurate estimation model during clear sky winter days is needed. The paper analyzes the measured values of the direct solar irradiance in the months of November from 2013 to2016 and, based on the daily received direct solar energy and the variability of the direct solar irradiance, the days are classified in four categories: clear sky days, partially clear sky days, partially cloudy days and cloudy days. In the entire monitoring period of four years (2013-2016) resulted 11 clear sky days for which, the measured values of the direct solar irradiance are comparatively analysed with the direct solar irradiance simulated with Meliss clear sky model. Further on, a statistical analysis is performed for the time interval 8:00-16:00 to evaluate absolute, relative and root mean square errors between the measured and simulated values. The results show that the simulation model underestimates, in nine out of the eleven clear sky days, the solar direct irradiance in the central part of the day. The measurements were performed in the Renewable Energy Systems and Recycling (RESREC) Research Centre located in the R&D Institute of the Transilvania University of Brasov, Romania.

Keywords: direct solar irradiance, clear sky simulation model, experimental assessment

1. INTRODUCTION

The use of solar energy for domestic hot water preparation and space heating is a topic that has been frequently approached. In the cold season, in temperate continental climate implementation sites, the monthly available solar energy is significantly lower than in the rest of the year. This is due to the limited number of clear- and partly clear sky winter days which, more than that, have less hours of daylight. To increase the solar fraction in the cold season, the surface of solar to thermal energy conversion systems should be increased accordingly. This has the main disadvantage that in the warm period the system is oversized and overheating occurs more frequent. For this reason it is necessary an accurate estimation of the hourly solar radiation profile during clear sky winter days to properly design the surface of the solar thermal collectors and to minimize the negative effects of overheating during summer. Several mathematical models were developed to estimate the available solar energy at the level of Earth’s surface, among these the most used are: sunshine-based models proposed by Angstrom [1] and Prescot [2], Meliss clear sky model [3], temperature-based models such the one developed by Abraha [5], the cloud-based models proposed by Badescu [4], and other meteorological parameters-based models [6].

To validate these models, researchers assessed experimental data measured in clear sky days in USA and Europe [7], Australia [8], Saudi Arabia [9], South Africa [10], China [11] and Brazil [12]. In Romania, Isvoranu and Badescu used experimental data from Romanian National Meteorological Administration for five stations (Iasi, Timisoara, Craiova, Cluj and Galati) to evaluate MM5 model of Dudhia [13], Mares, Vizman and Paulescu used values measured on the Solar Platform of the West University of Timisoara [14] with a model defined by Badescu [15], Condurache-Bota and Florea evaluated the evolution of the UV irradiance at ground level between 1979 and 2013 [16]. For the mountain continental temperate climate of Brasov, the German model Meliss [3] was tested for summer period, the results showing that the model overestimates in eleven out of the thirteen clear sky days identified in the July months of the 2013-2016 monitoring interval [17]. The reliability of this model is further investigated for the winter months too.

Thus, the clear sky Meliss model [3] is compared in this paper with onsite measured direct solar irradiance for a winter month (November). The measurements were performed in the Renewable Energy Systems and Recycling (RESREC) Research Centre located in the R&D Institute of the Transilvania University of Brasov, Romania. All the days of November 2016 were analysed and, based on the daily received direct solar energy and imposing a low degree of variability for the direct solar irradiance, the days were classified in four categories: clear sky days, partially clear sky days, partially cloudy days and cloudy days. Thus, only four days were found as clear sky days in November 2016. Similarly, the months of November 2013, 2014 and 2015 were analysed resulting 11 clear sky days in the entire monitoring period of four years (2013-2016). Absolute, relative and root mean square errors between the measured and simulated values were statistically analysed for the time interval 8:00-16:00, the results showing that the simulation model underestimates, in nine out of the eleven clear sky days.

2. METHOD

The method relies on experimental data measured with a Kipp&Zonen Solys2 Sun Tracker installed since 2013 on the rooftop of the Laboratory building of the Renewable Energy Systems and Recycling (RESREC) Research Centre located in the R&D Institute of the Transilvania University of Brasov, Romania. This device has a pointing accuracy $<0.1°$ and is equipped with a First Class CHP1 pyrheliometer having a daily uncertainty $< \pm 1\%$ in measuring the direct solar irradiance with a sample rate of 15 seconds, out of the 4 measurements per minute the minimum, average, maximum and standard deviation are stored in a database each minute. To avoid incidental shadings of the instruments (e.g. by birds flying over the instruments), the maximum value of the direct solar irradiance recorded for each minute “*i*” ($B_{exp,\ i}$) was considered. To further classify the days, these measured values were used to approximate the received direct solar energy over a period of time between t_1 and t_2 (apparent solar time converted from local standard time using the well-known equation of time and longitude correction [18]), considering the direct solar irradiance ($B_{exp,\ i}$) constant over a time interval τ of one minute between two measurements, with:

$$\boldsymbol{E_{B_{exp}} = \frac{1}{60}\sum_{i=t_1}^{t_2} B_{exp,i}\,\tau}, \text{ [Wh/m}^2\text{]} \quad (1)$$

The time interval [t_1, t_2] was firstly considered as between 07:00 – 17:00 to evaluate the daily available direct solar energy, in November the sunrise occurring between 07:00 and 08:00 and the sunset 16:00 and 17:00. Further on, the interval 08:00 – 16:00 is of interest, to compare the results with the experimental findings previously obtained for summer months of July 2013-2016 [17]. In contrast with July, the maximum solar elevation range is lower in November (24.97°) as well as the solar azimuthal angle ranging between 55.13° at 8:00 and -55.13° at 16:00. The variation of solar angles combined with the fixed angles of the south oriented solar convertors (38° elevation angle, 0° azimuthal angle) optimally tilted for Brasov (on a yearly basis) generates incidence angles as high as 59.64° (at 8:00 and 16:00) with the minimum value of 13.03° at noon. The higher the incidence angle, the lower the received solar radiation is.

For the "***k***" number of the clear sky days identified during the monitoring period the mean experimental direct solar irradiance for each minute "*i*" ($B_{exp\_m,i}$) and the corresponding mean experimental received direct solar energy ($E_{Bexp\_m,\ i}$) are further calculated with:

$$\boldsymbol{B}_{\mathbf{exp\_m},i} = \frac{\sum_{j=1}^{k} B_{exp,j}}{k}, \text{ [W/m}^2\text{]} \tag{2}$$

$$E_{B_{exp\_m}} = \frac{1}{60}\sum_{i=t_1}^{t_2} B_{\mathbf{exp\_}m,i}\,\tau, \text{ [Wh/m}^2\text{]} \tag{3}$$

Further on, Meliss clear sky model [3] is used to simulate each minute "i" the direct solar irradiance at ground level (B_i) for Brasov, 45.67°N latitude and 25.55°E longitude, with:

$$B_i = B_0 \cdot e^{\left(\frac{-T_R}{0.9+9.4\sin\alpha_i}\right)}, \text{ [W/m}^2\text{]} \tag{4}$$

where: B_0 is the solar irradiance at the upper limit of the Earth's atmosphere ranging between 1413 W/m² corresponding to the smallest Earth-Sun distance attained in 3rd of January and 1321 W/m² for the farthest Earth-Sun position in 3rd of July [17], T_R is the turbidity factor having site-dependent monthly values between 2.8 and 3.2 for Brasov region [19, 20], α is the solar elevation angle varying daily between zero (at sunrise and sunset) and a maximum value at noon, seasonally dependent: highest value at summer solstice and smallest values at winter solstice [21].

The direct solar energy (E_B) is then approximated with:

$$E_B = \frac{1}{60}\sum_{i=t_1}^{t_2} B_i \cdot \tau, \text{ [Wh/m}^2\text{]} \tag{5}$$

To compare the experimental with the simulated values of the direct solar irradiance, the absolute ($\varepsilon_{B,i}$), mean absolute ($\varepsilon_{Bm,i}$), relative ($\varepsilon_{rB,i}$) and mean relative ($\varepsilon_{rBm,i}$) errors are calculated with:

$$\varepsilon_{B,i} = B_{exp,i} - B_i, \text{ [W/m}^2\text{]} \tag{6}$$

$$\varepsilon_{Bm,i} = B_{exp\ m,i} - B_{m,i}, \text{ [W/m}^2\text{]} \tag{7}$$

$$\varepsilon_{rB,i} = \frac{\varepsilon_{B,i}}{B_{exp,i}} \cdot 100, \text{ [\%]} \tag{8}$$

$$\varepsilon_{rBm,i} = \frac{\varepsilon_{Bm,i}}{B_{expm,i}} \cdot 100, \text{ [\%]} \tag{9}$$

Further, the absolute (RMSE) and relative (rRMSE) root mean square errors between experimental ($B_{exp,\ i}$) and simulated (B_i) direct solar irradiance for the "n" samples over the considered time interval are calculated with:

$$\boldsymbol{RMSE} = \sqrt{\frac{\sum_{i=1}^{n}(B_{exp,i} - B_i)^2}{n}}, \text{ [W/m}^2\text{]} \tag{10}$$

$$\boldsymbol{rRMSE} = \sqrt{\frac{\sum_{i=1}^{n}(\varepsilon_{rB,i})^2}{n}}, \text{ [\%]} \tag{11}$$

In the same way, the absolute (ε_E) and relative (ε_{rE}) errors between the experimental (E_{Bexp}) and simulated (E_B) and the mean absolute (ε_{E_m}) and mean relative (ε_{rE_m}) errors between mean experimental (E_{Bexp_m}) and mean simulated (E_{B_m}) received direct solar energy are calculated with:

$$\varepsilon_E = E_{B_{exp}} - E_B, \text{ [Wh/m}^2\text{]} \tag{12}$$

$$\varepsilon_{rE} = \frac{\varepsilon_E}{E_{B_{exp}}} \cdot 100, \text{ [\%]} \tag{13}$$

$$\varepsilon_{E\_m} = E_{B_{exp\_m}} - E_{B\_m}, \text{ [Wh/m}^2\text{]} \tag{14}$$

$$\varepsilon_{rE\_m} = \frac{\varepsilon_{E\_m}}{E_{B_{exp\_m}}} \cdot 100, \text{ [\%]} \tag{15}$$

3. RESULTS AND DISCUSSION

The daily direct solar energy was evaluated with eq. (1) for November 2016. Based on the results plotted in decreasing order in Figure 1, three thresholds were established to categorize the days in four types: clear sky, partially clear sky, partially cloudy and cloudy days.

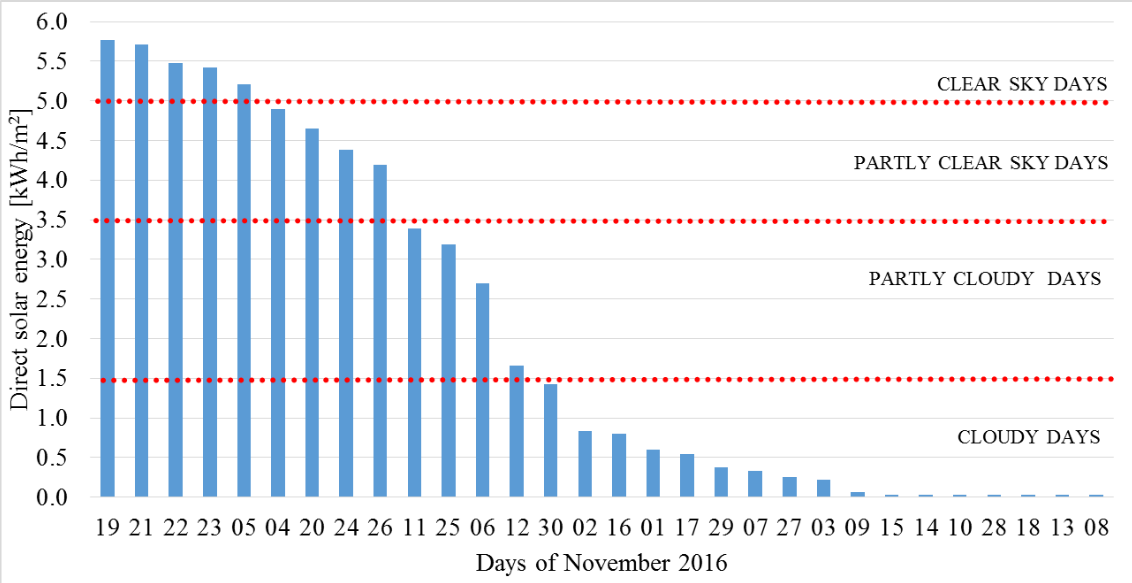


Fig.1. Classification of November 2016 days sorted by daily direct solar energy

For each category of days, eq. (2) was used to calculate the mean value of the experimental direct solar irradiance (B_{exp_m}), resulting four curves: B_{exp_m1} for the five clear sky days, B_{exp_m2} for the four partially clear sky days, B_{exp_m3} for the four partially cloudy days and B_{exp_m4} for the seventeen cloudy days. The four mean experimental curves and the simulated direct solar irradiance (B) obtained for 21th of November 2016 are plotted in Figure 2.

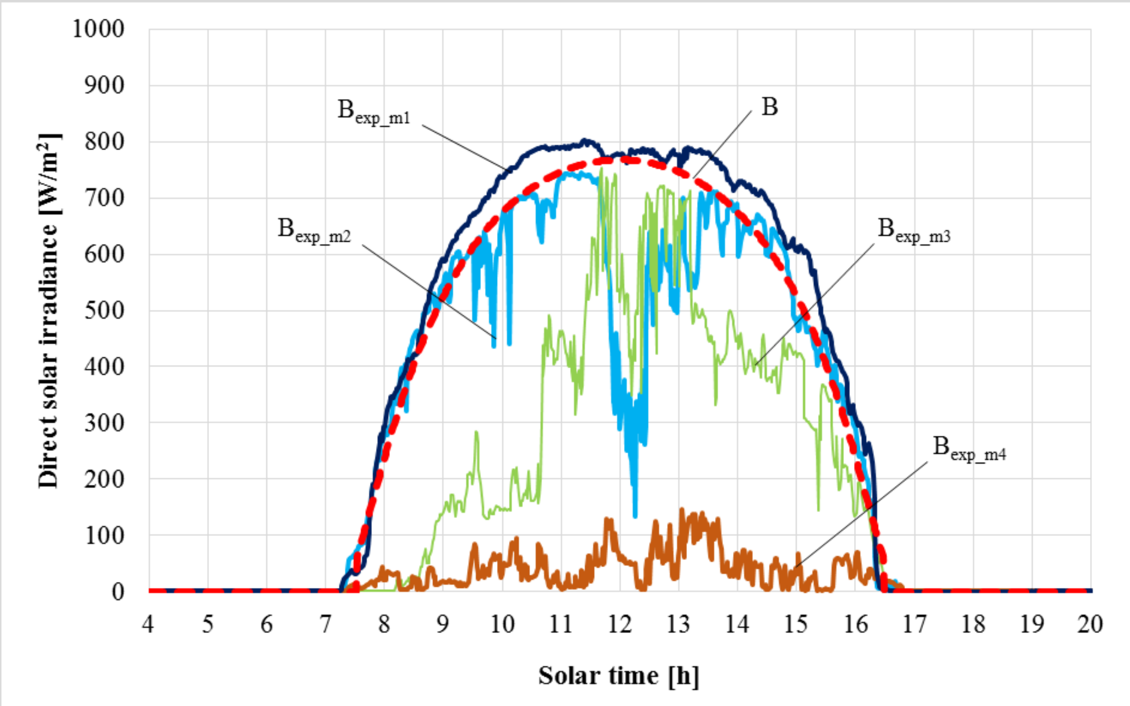


Fig. 2 Mean experimental and simulated direct solar irradiance daily variation in November 2016

Supplementary, analysing the variability of the direct solar irradiance during each clear sky day of November 2016, 5th of November was excluded and only four days were finally identified as clear sky days in November 2016. The same procedure was applied to identify the clear sky days for the months of November in 2013, 2014 and 2015 resulting in total eleven clear sky days as presented in Table 1 and in Fig.3. In 08.11.2013, even if few drops occurred in solar irradiance, the day was considered in the error analysis, this being the only clear sky day in 2013.

Table 1. The number of clear sky in November days in monitoring interval (2013 – 2016)

Year	2013	2014	2015	2016	2013-2016
No. of clear sky days in November	1	2	4	4	11

For each clear sky day in November 2013 – 2016, the direct solar irradiance (B_i) was calculated with eq. (4) and, averaging the obtained values for each minute "i", a mean direct solar irradiance resulted (B_m), plotted in Fig. 3 against the mean experimental direct solar irradiance ($B_{exp\ m}$) obtained from all experimental values (B_{exp}). The Meliss model generated underestimations of the direct solar irradiance in the 8:00 – 16:00 interval, excepting 3rd and 4th of November 2014. The underestimations have a maximum absolute error of 377.14 W/m² between experimental (B_{exp}) and simulated (B_i) values in 01.11.2015, and 139.22 W/m² between mean experimental ($B_{exp\ m}$) and simulated (B_m) values resulting that the use of the mean experimental direct solar irradiance ($B_{exp\ m}$) improves the accuracy of the simulation.

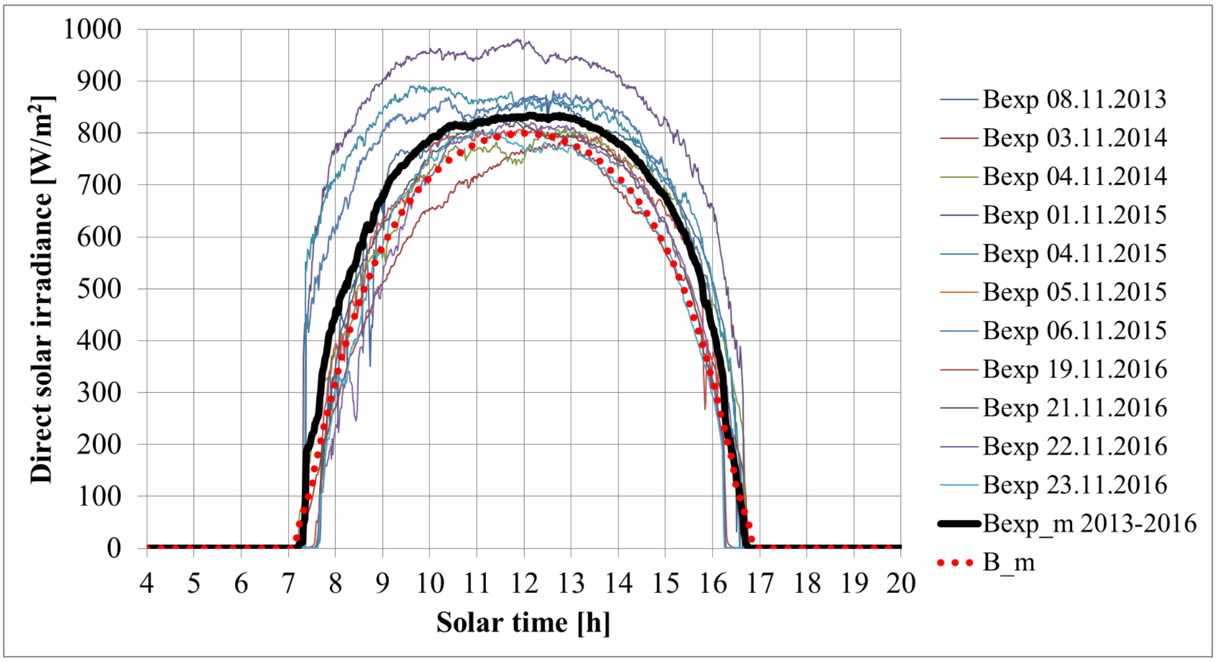
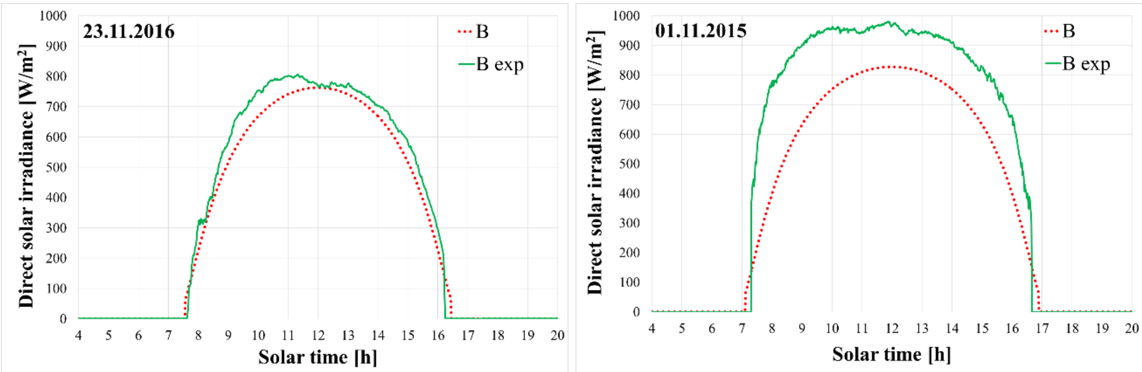


Fig.3 Simulated and experimental direct solar irradiance: November 2013-2016

Two out of the eleven clear sky days were selected and separately plotted in Fig. 4 along with the simulated direct solar irradiance. In 23th of November 2016 (Fig. 4a), during 08:00-16:00 interval, the simulated values were close but still underestimated by the experimental values, with lower absolute errors in the morning and in the evening, the maximum absolute error 97.12 W/m² occurring in the central part of the day. In 1st of November 2015 (Fig.4b), the model largely produced underestimations, the maximum absolute error being 377.14 W/m².

Further, for the 11 clear sky days in November 2013-2016, the maximum absolute and maximum relative errors between experimental ($B_{exp,\ i}$) and simulated (B_i), and between mean experimental ($B_{exp\ m,\ i}$) and mean simulated ($B_{m,\ i}$) direct solar irradiance in 8:00-16:00 interval are presented in Table 2 along with the absolute and relative root mean squared errors calculated for a number of 480 samples over the considered interval.



a) b)

Fig. 4 Simulated and experimental direct solar irradiance in the two selected clear sky days

Table 2. Errors between experimental and simulated direct solar irradiance (8:00-16:00)

Day	max $\varepsilon_{B,i}$ [W/m²]	max $\varepsilon_{Bm,i}$ [W/m²]	max $\varepsilon_{rB,i}$ [%]	max $\varepsilon_{rBm,i}$ [%]	RMSE [W/m²]	rRMSE [%]
08.11.2013	-191.98		-54.75		81.83	12.68
03.11.2014	-117.27		-41.21		74.40	14.20
04.11.2014	101.63		20.36		45.19	7.20
01.11.2015	377.14		48.55		198.00	23.09
04.11.2015	347.97		48.15		139.90	18.05
05.11.2015	259.39	135.14	41.43	29.54	119.41	16.23
06.11.2015	267.39		44.73		143.67	20.36
19.11.2016	208.03		39.32		84.61	14.31
21.11.2016	135.60		32.79		81.13	14.06
22.11.2016	-133.56		-54.50		69.35	12.70
23.11.2016	97.12		28.52		55.30	9.65

Analysing data presented in Table 2, in eight days were obtained positive and high (between 97.12 W/m² and 377.14 W/m²) absolute errors, even the mean absolute error is positive and high (135.14 W/m²) showing an important deviation of the simulation values in the 08:00-16:00 time interval. These correspond to high relative errors with values ranging between 20.36% and 48.55%, with a mean relative error of 29.54%. The negative absolute errors (between -117.27 W/m² and -191.98 W/m²) and relative errors (between -41.21% and -54.75 %) correspond to the direct solar irradiance drops which, if excluded, will reduce the number of considered clear sky days. The absolute root mean square errors range between 45.19 W/m^2 and 198 W/m^2, inducing relative root mean square errors between 7.20 % and 23.09 %. Thus, acceptable relative root mean square errors (<5%) were not obtained, values between 5% and 10% were obtained only for two days, and higher than 10% for the rest of nine days showing that the model does not provide accurate simulations for the 08:00-16:00 time interval. To evaluate if the model under- or overestimates the direct solar irradiance, absolute and relative errors were calculated. Thus, the results show a high level of underestimation of the Meliss model for November months.

Further, the daily experimental, mean experimental and simulated direct solar energy were calculated, with eq. (1), (3) and (5) and the results obtained for the time interval 8:00-16:00 are comparatively presented in table 3, along with the associated errors calculated based on eq. (12-15).

Table 3. Simulated and experimental direct solar energy and associated errors (8:00-16:00)

Day	E_B [KWh/m²]	$E_{B_{exp}}$ [KWh/m²]	$E_{B_{exp\,m}}$ [KWh/m²]	ε_E [KWh/m²]	$\varepsilon_{E\,m}$ [KWh/m²]	ε_{r_E} [%]	$\varepsilon_{r_{E\,m}}$ [%]
08.11.2013	5.43	5.97		0.54		9.12	
03.11.2014	5.60	5.06		-0.55		-10.80	
04.11.2014	5.57	5.57		0.01		0.10	
01.11.2015	5.67	7.19		1.52		21.10	
04.11.2015	5.57	6.51		0.94		14.38	
05.11.2015	5.53	6.36	5.90	0.83	0.56	13.09	9.49
06.11.2015	5.50	6.36		0.87		13.65	
19.11.2016	5.02	5.60		0.58		10.29	
21.11.2016	4.96	5.57		0.61		10.91	
22.11.2016	4.94	5.37		0.44		8.13	
23.11.2016	4.91	5.31		0.40		7.54	

In the clear sky days in the months of November 2013-2016, the experimentally evaluated direct solar energy ranges between 4.91 kWh/m^2 and 5.67 kWh/m^2 over the time interval 08:00-16:00. Comparing these values with the direct solar energy obtained based on simulations, the absolute errors between -0.55 kWh/m^2 and 1.52 kWh/m^2 were obtained increasing the relative errors up to 21.10% which is not acceptable in the design process of the solar thermal systems. Using the mean values of the experimentally obtained direct solar energy can be a solution to alleviate this large simulation underestimation. An absolute error of 0.56 kWh/m^2 between mean experimental and mean simulated direct solar energy was obtained, corresponding to a relative error of 9.49 % which is still substantial particularly in the case of large solar converting systems.

The direct solar energy was similarly calculated for 7:00-17:00 interval and the results are presented in table 4 along with associated errors, showing mainly positive absolute errors but also a negative one. The positive absolute errors obtained both in 08:00-16:00 and 07:00-17:00 intervals indicate that the simulation model underestimated the direct solar irradiance in the clear sky days of November analysed months. The days with negative absolute errors in 07:00-17:00 interval, corresponds to solar direct irradiance drops. The fact that the mean absolute error in 07:00-17:00 interval (0.65 kWh/m^2) is not significantly higher than the one obtained in the 08:00-16:00 interval (0.56 kWh/m^2) indicates that the deviations are higher in the central interval of the day.

Table 4. Simulated and experimental direct solar energy and associated errors (7:00-17:00)

Day	E_B [KWh/m²]	$E_{B_{exp}}$ [KWh/m²]	$E_{B_{exp\,m}}$ [KWh/m²]	ε_E [KWh/m²]	$\varepsilon_{E\,m}$ [KWh/m²]	ε_{r_E} [%]	$\varepsilon_{r_{E\,m}}$ [%]
08.11.2013	5.72	6.26	6.25	0.54	0.65	8.61	10.32
03.11.2014	5.98	5.34		-0.64		-11.96	
04.11.2014	5.92	6.00		0.07		1.18	
01.11.2015	6.09	7.93		1.84		23.20	
04.11.2015	5.92	7.11		1.19		16.72	
05.11.2015	5.87	6.85		0.98		14.34	
06.11.2015	5.82	6.85		1.03		15.09	
19.11.2016	5.18	5.78		0.61		10.48	
21.11.2016	5.10	5.72		0.62		10.80	
22.11.2016	5.06	5.49		0.42		7.70	
23.11.2016	5.03	5.42		0.40		7.28	

4. CONCLUSIONS

All days in November months of a four years monitoring period (2013-2016) were analysed in terms of the direct solar irradiance on-site measured in the Renewable Energy Systems and Recycling Research Centre of the R&D Institute of the Transilvania University of Brasov, Romania. Experimental direct solar energy was calculated and based on, the days were sorted in four categories: clear sky, partially clear sky, partially cloudy and cloudy days. The variability of the direct solar irradiance was also considered. The measured direct solar irradiance measured in the clear sky considered days were further compared with simulated values obtained with Meliss clear sky model. Excepting two out of the total of eleven clear sky days, the model underestimates the direct solar irradiance with a mean absolute error of 135.14 W/m² corresponding to a mean relative error of 29.54 % in the time interval 08:00-16:00. The mean absolute and relative errors between measured and simulated direct solar energy in the same interval of time is 0.56 kWh/m² and respectively 9.49 %. When considering the direct solar energy received during the whole daylight interval (07:00-17:00), the mean absolute error only increases to 0.65 kWh/m² showing the importance of an accurate estimation in the central part of the day (08:00-16:00). Thus, the underestimation provided by the Meliss model in the winter months of November is highlighted, in contrast with summer months when a previous study [17] showed that the Meliss model overestimate the solar irradiance in clear sky days. Therefore, the accuracy of Meliss clear sky model should be further improved mainly in the central part of the day (08:00-16:00) when the largest differences were obtained. Also, further research will be developed for the morning and afternoon periods of time as well as to define a new model able to simulate the solar irradiance for the other types of days, by analysing measured and simulated data on the entire year. A methodology will be proposed to be applied also for other locations.

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