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Estimation of Solar Irradiation on Inclined Surface Based on Web Databases

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***Abstract*—Estimation of Global Tilted Irradiation (GTI) is a key to performance assessment of typical solar systems since they usually employ tilted photovoltaic (PV) modules or collectors. Numerous solar radiation databases can deliver irradiation values both on horizontal and tilted plane, however they are validated mostly with horizontal-plane ground measurements. In this paper we have compared GTI estimates retrieved from five Internet databases with results of measurements at two PV systems located in Poland. Our work shows that in spite of good agreement in annual scale, there is a tendency to underestimate GTI in summer and overestimate in winter, when PV modules can receive less than a half of expected irradiation. The latter issue affects sizing of PV system components and implies a correction needed to achieve all-year long operation.**

***Keywords*—Solar Radiation Databases, Global Tilted Irradiation, Photovoltaics, Array and Battery Sizing**

I. Introduction

ESTIMATION of solar resource is essential in design of every solar system. It has impact to system siting, sizing of components (like solar modules and battery), energy yield and also reliability of the system. This task is much easier nowadays because numerous spatially-distributed solar radiation databases are available as a result of European, national or commercial projects. A survey regarding methods and tools presently available to determine potential of renewable sources (e.g. solar and wind) can be found in [1]. Yearly sums of global irradiation from six spatial databases have been compared in [2]. Different satellite-based surface solar irradiation databases have been also presented and compared in [3]. Access to those databases is usually granted via web interface. Two basic methods of solar irradiation estimation are employed to collect data: ground measurements and calculations based on satellite images.

In case of ground measurements, we have to relay on results from meteorological ground stations with nonuniform spatial distribution. These stations usually provide high-quality data. However, in case of sites distant from ground measuring stations, interpolation or extrapolation of data is necessary which in turns decreases accuracy. Satellite-based services, on the other hand, provide maps of solar irradiation for extensive geographical area (especially when geostationary satellites are employed) with spatial resolution ranging from 1 to 280 kilometers [3]. This method can provide fine spatial and temporal resolution, but also has some disadvantages. Snow, frost or ice coverage of the ground can mislead the estimation algorithm since such areas may look as they were cloud-covered, and some auxiliary information is needed in such cases [4], [5]. Low sun angles also lead to estimation errors, as well as locations in mountains and in some coastal zones [2]. Accuracy of the satellite-based method also declines with increasing latitude because geostationary satellites see the earth's surface at an increasingly unfavourable angle [6].

Many solar databases can provide irradiation data both on horizontal and inclined planes. Horizontal plane irradiation is a primary source of data because typical meteorological data sets are measured using horizontal irradiance sensors [7]. Next step is calculation of Global Tilted Irradiation (GTI) that involves decomposition of radiation components and employs a selected transposition model [8]. Unfortunatelly, these procedures introduce additional errors. Despite lower accuracy, GTI estimates are much more important from practical point of view. PV modules are normally mounted at an angle (inclination) from horizontal [7] in order to maximize the energy yield, and their performance is not fully determined just by global horizontal radiation [9]. Therefore, prediction of tilted (or *plane-of-array*) irradiation is a key to performance assessment of typical solar systems.

Quality of solar databases has been validated in many research programs. Five satellite databases have been validated against data from 23 ground sites in [10], unfortunately without any site from central Europe. Cross-comparison of six databases (ESRA, PVGIS, Meteonorm, Satel-Light, Helioclim-2, NASA SSE) has been presented in [2]. Satel-Light database has been validated during two years (1996-1997) in Bergen [6] and in other Scandinavian ground stations [4]. In [9], new solar radiation data calculated from satellite images in Climate Monitoring Satellite Application Facility (CM-SAF) has been compared with classic PVGIS database based on ground measurements. Comparison of other satellite database (obtained from GOES satellite images) with high quality ground-measured data from Kimberly, Idaho in United States can be found in [5].

The accuracy reported for databases varies from one study to another, depending on considered location and time period, and it is therefore very difficult to draw general conclusions. Most of the research focus on global horizontal irradiation (GHI) and only a few papers reports estimation errors of GTI. The performance of different GTI estimation methods has been evaluated in [8] and compared with results of precise measurements carried out in Golden, Colorado (United States). Historical estimates of solar radiation from geostationary satellites have been compared in [11] with results of ground measurements performed in Colorado with rotating shadowband radiometers. It has been found that the performance of all solar radiation transposition models degrade significantly when only

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global horizontal irradiance is measured and direct and diffuse components need to be estimated. Therefore, further research is needed to improve the process of predicting irradiance on tilted planes in realistic situations [8].

The aim of our work is to check usefulness of GTI estimates from different open-access databases for central Europe locations. To achieve this goal we have compared monthly averages of daily global irradiation on a tilted plane obtained from five Internet databases with results of ground measurements from two independent sites located in Poland.

II. Solar Radiation Databases

For this work we have selected open-access databases available via web servers. Additional criterion was the availability of global tilted-plane irradiation (GTI) data. In Tab. I, II we have summarized the considered databases.

PVGIS-CMSAF is a relatively new database for Europe, Africa and part of Asia. It delivers estimates based on calculations from Meteosat and MSG satellite images and represents a total of 12 years of data [9], [12]. Previous version of this database (PVGIS-3) employs interpolation of results from ground station measurements collected during 10 years in the European Solar Radiation Atlas, and is available on the same website. Both databases can be used to evaluate performance of stand-alone and grid-connected PV systems via simple user interface.

Satel-Light database is an outcome of a project supported by the European Commission. It also employs Meteosat images and covers 5 years of data [2] recorded in half-hour periods. Detailed information on solar radiation (for example statistical distributions) at numerous sites located in western and central Europe can be retrieved from the website.

NASA-SSE database employs 25 years of data from Global Energy and Water Exchanges Surface Radiation Budget (GEWEX SRB) Project [13]. These datasets are produced using cloud parameters derived from International Satellite Cloud Climatology Project (ISCCP) and meteorological inputs from GMAO reanalysis datasets with radiative transfer algorithms. The database provides GTI estimates only for selected tilt angles related to latitude.

Helioclim-3 database is a part of commercial SoDa Service [14] that offers on-demand solar radiation data in fine spatial and temporal resolution. This database is constantly updated since 2004. Two years of GTI data is available for free download and has been processed in our research. More recent results are provided on-demand as a commercial service.

TABLE I
Selected databases and their websites

Name	Website
PVGIS-CMSAF	http://re.jrc.ec.europa.eu/pvgis
PVGIS-3	http://re.jrc.ec.europa.eu/pvgis
Satel-Light	http://www.satel-light.com
NASA-SSE	https://eosweb.larc.nasa.gov/sse
HelioClim-3	http://www.soda-is.com

TABLE II
Parameters of selected databases

Database	Method	Time range
PVGIS-CMSAF	Satellite	1998-2011
PVGIS-3	Ground	1981-1990
Satel-Light	Satellite	1996-2000
NASA-SSE	Satellite	1983-2007
HelioClim-3	Satellite	2004-2005*

(*) Further data available commercially.

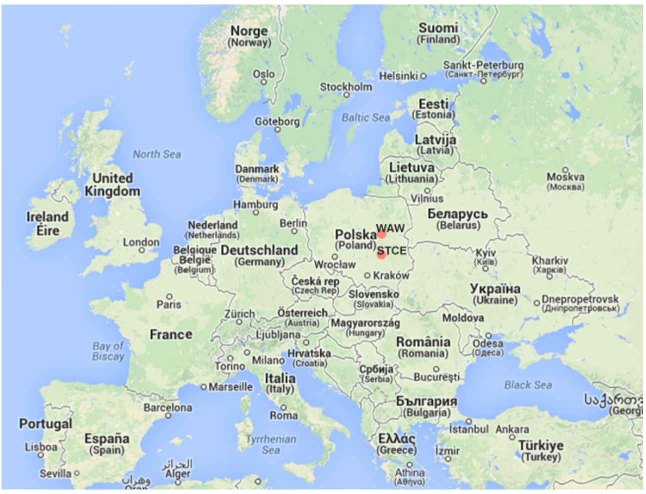

Fig. 1. Geographical location of ground stations (source: https://maps.google.com/)

III. Ground Station Measurements

Ground measuremets have been carried out in two independent stations located in Poland. Location of the stations is shown in Fig. 1 and their details are given in Tab. III.

TABLE III
Details of ground stations

Site (Time range)	Latitude	Longitude	Elev. [m]	Tilt Angle
WAW (2003-2007)	52°09'N	21°12'E	143	30°
STCE (2012-2014)	51°03'N	21°04'E	264	51°

The first station (WAW) is placed in Warsaw and it is a part of grid-tied PV system installed on the roof of the public school [15], [16]. The plane of PV modules is facing south and is tilted at 30° from horizontal in order to improve annual energy production. Irradiance in the plane of PV array is measured by a silicon reference cell (Spektron 100) [17]. The performance of the system has been monitored according to the standard IEC 61724 since the time of installation. In our research we have processed five years of GTI data from this location.

The second station (STCE) is located in Starachowice on the flat roof of two-storey building [18]. Irradiance is measured with using a commercial 5-Watt polycrystalline silicon module (Celline CL005-12P) facing south and tilted at 51°, as shown in Fig. 2. Main parameters of the solar module are summarized in Tab. IV. Module power has been rated for Standard Test Conditions (STC, irradiance 1000 W/m^2, temperature 25 °C, air mass 1.5). In this location, tilt angle has been selected to improve performance of a stand-alone PV system during autumn and winter [19]. There are no near obstacles (like trees or buildings) that could cause shading. The solar module has been inspected and cleaned regularly. All the maintenance procedures have been carried out during nights only, in order to keep consistency of records. In our research we have collected and processed over two years of GTI data.

Fig. 2. Experimental PV module installation (second site)

TABLE IV
Experimental solar module parameters

Parameter	Symbol	Value
Rated power	P_{max}	5 W
Rated current	I_{mpp}	0.30 A
Rated voltage	V_{mpp}	16.5 V
Short-circuit current	I_{sc}	0.34 A
Open circuit voltage	V_{oc}	21.0 V
Number of PV cells		36
Dimensions		350 x 180 x 17 mm

In both stations, global tilted irradiance $G_t(n,i)$ is measured once per five minutes and stored in internal memory of Data Acquisition System (DAS). Measurement results are periodically downloaded in order to aggregate and obtain monthly averages of daily irradiation values in kWh/m^2/day:

$$H_t(m) = \frac{1}{N_d(m)} \sum_{n=1}^{N_d(m)} \sum_{i=1}^{N_s} G_t(n,i) T_s, \quad (1)$$

where T_s is a sampling period ($T_s = 1/12$ h), N_s is a number of samples collected during n-th day in the month , and $N_d(m)$ is a number days in m-th month ($m = 1, \ldots, 12$). The irradiation values (1) calculated for each month are afterwards averaged over all years of available data. Finally, average annual irradiation on inclined surface is calculated in kWh/m^2 as a sum of monthly irradiations:

$$H_{ty} = \sum_{m=1}^{12} N_d(m) H_t(m). \quad (2)$$

IV. Results Comparison and Discussion

In Tab. V we have compared annual irradiation values obtained in ground-measured value at the first site with estimates retrieved from Internet databases. Relative difference is shown in percentages (positive differences mean that the database estimates are higher than the ground-measured value). Estimated values of annual irradiation fit very close to results of ground measurements and the differences are within 5% of instrumental uncertainty limits [17]. Two databases (Helioclim-3, Satel-Light) have delivered the best estimates of global tilted irradiation, with differences lower than 2%. There is a substantial difference (9.1%) between the results from the two PVGIS databases. It is widely known [12], however, that the new PVGIS-CMSAF database provides global irradiation values higher than the classical PVGIS-3 at the large majority of validation points. Discussion of these differences may be found in [9].

In Tab. VI we have compared in the same way the annual irradiation values for the second site. Again, there is a remarkable difference (7.6%) between the results from both PVGIS databases. The differences from all databases have also not exceeded 5% and are of the order of a commercial PV module power rating deviations [20]. The best estimate of global tilted irradiation (with 1.2% difference) has been delivered from HelioClim-3 database.

TABLE V
Average annual irradiation (H_{ty}) on inclined surface (WAW)

Data Source	Global irradiation [kWh/m^2]	Difference [%]
Ground-measured	1216	
PVGIS-CMSAF	1270	4.5
PVGIS-3	1160	-4.6
Satel-Light	1192	-1.9
NASA-SSE	1168	-3.9
HelioClim-3	1227	0.9

TABLE VI
Average annual irradiation (H_{ty}) on inclined surface (STCE)

Data Source	Global irradiation [kWh/m^2]	Difference [%]
Ground-measured	1177	
PVGIS-CMSAF	1230	4.5
PVGIS-3	1140	-3.1
Satel-Light	1139	-3.2
NASA-SSE	1135	-3.5
HelioClim-3	1191	1.2

In Tab. VII and in Fig. 3 we have presented monthly mean of daily irradiation obtained from ground measurements and retrieved from databases for the first site. The shapes of plots

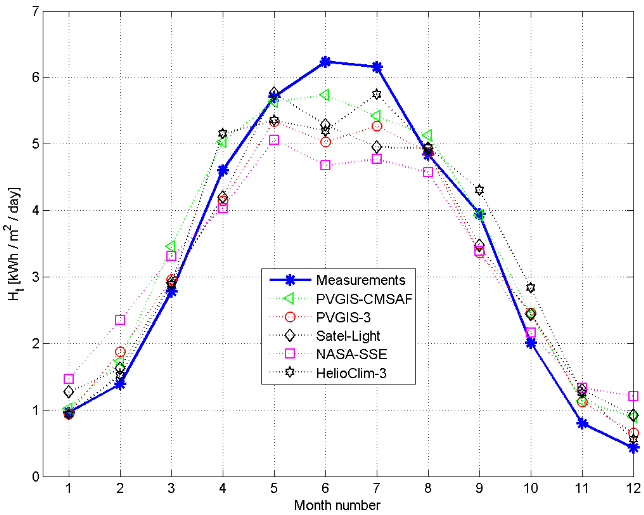

Fig. 3. Measured and estimated average daily irradiation (WAW)

are similar to each other, but the ground-measured irradiation in June and July is noticeably higher than database predictions. This suggests that the real radiation components are higher than the estimated values, or the tranposition model (employed in databases for calculation of GTI) is not accurate enough in such conditions. Opposite tendency is clearly visible during autumn and winter months – ground-measured GTI values are distinctly lower than these obtained from databases.

TABLE VII
MONTHLY AVERAGES OF DAILY GTI VALUES (H_t) FROM DIFFERENT SOURCES (WAW)

Month	Ground	PVGIS -CMSAF	PVGIS -3	Satel- -Light	NASA- -SSE	HC-3
1	1.0	1.0	0.9	1.3	1.5	0.9
2	1.4	1.7	1.9	1.6	2.4	1.5
3	2.8	3.5	3.0	2.9	3.3	2.9
4	4.6	5.0	4.1	4.2	4.0	5.2
5	5.7	5.6	5.3	5.8	5.1	5.4
6	6.2	5.7	5.0	5.3	4.7	5.2
7	6.2	5.4	5.3	5.0	4.8	5.8
8	4.8	5.1	4.9	4.9	4.6	4.9
9	3.9	3.9	3.4	3.5	3.4	4.3
10	2.0	2.5	2.5	2.4	2.2	2.8
11	0.8	1.1	1.1	1.3	1.3	1.3
12	0.4	0.9	0.7	0.9	1.2	0.6

Relative differences between GTI values from databases and results of ground measurements at the first location are summarized in Tab. VIII (positive differences mean that the values from databases exceed these from measurements). The second column shows a number of days with available results for each month, gathered during all years of observation.

The estimates for December from databases other than PVGIS-3 and Helioclim-3 can be as much as 107…181% higher than the real values measured on the ground. Such huge relative differences result from low level of absolute irradiation values and vulnerability to estimation or measurement errors.

The effect of GTI overestimation in winter may be a result of low sun altitudes and unfavorable changes of sunlight spectrum [7] during winter. Similar phenomenon has been

TABLE VIII
RELATIVE DIFFERENCES OF MONTHLY IRRADIATION IN % (WAW)

Month	Days	PVGIS -CMSAF	PVGIS -3	Satel- -Light	NASA- -SSE	HC-3
1	155	6.1	-2.2	32.0	51.9	-2.9
2	141	24.8	34.9	17.3	69.6	9.6
3	155	24.5	6.5	5.0	19.1	3.9
4	150	9.3	-10.1	-8.8	-12.5	12.0
5	155	-1.4	-6.4	0.9	-11.3	-6.2
6	150	-7.9	-19.3	-15.2	-24.9	-16.7
7	155	-12.0	-14.4	-19.5	-22.5	-6.6
8	155	6.1	0.7	2.0	-5.5	2.3
9	150	-0.7	-14.9	-12.0	-14.1	9.1
10	155	21.8	22.3	21.4	7.4	41.0
11	150	41.8	40.6	63.4	66.9	57.8
12	155	107.0	51.2	113.3	181.4	29.2

reported in Bergen, Norway [6], where irradiance estimates based on METEOSAT images have exceeded ground measurements under overcast sky, while the opposite statement has been true under approximately cloudfree sky. These discrepancies can be caused by the fact that satellites deliver data in broadband spectrum, while silicon PV cells employed in ground measurements have narrow-band sensitivity [8]. In a year's scale, the estimation errors in winter and in summer compensate each other giving an accurate estimate of annual irradiation.

In Tab. IX we have summarized monthly means of daily irradiation (in kWh/m^2) from our second site, in comparison with values delivered from different databases. The same values are also shown in Fig. 4. Shapes of the plots are quite similar to each other in exception for a pair of months. In July the irradiation estimates from all databases during consecutive three years are lower than ground-measured value, and in January the opposite phenomenon takes place. Relative differences between GTI forecasts from databases and results of ground measurements are summarized in Tab. X.

TABLE IX
MONTHLY AVERAGES OF DAILY GTI VALUES (H_t) FROM DIFFERENT SOURCES (STCE)

Month	Ground	PVGIS -CMSAF	PVGIS -3	Satel- -Light	NASA- -SSE	HC-3
1	0.6	1.2	1.3	1.6	1.6	1.3
2	1.8	2.0	2.2	1.9	2.5	1.6
3	3.3	3.6	3.1	3.1	3.4	3.2
4	4.0	4.8	3.9	3.9	3.8	4.9
5	4.6	5.0	4.7	4.9	4.6	4.7
6	4.6	4.9	4.4	4.5	4.2	4.8
7	5.1	4.7	4.7	4.2	4.3	4.8
8	4.7	4.8	4.5	4.4	4.3	4.5
9	4.0	3.9	3.4	3.4	3.3	4.7
10	3.2	2.8	2.8	2.5	2.3	3.2
11	1.2	1.4	1.4	1.5	1.5	1.3
12	1.5	1.2	0.9	1.3	1.3	0.8

In January, the values of GTI from databases were 119…194% higher than the result of measurements which means that the PV module received less than a half of expected irradiation. On the other hand, the values retrieved from databases for July were 7…18% lower than the ground measurements. The differences compensate in scale of a year

TABLE X
RELATIVE DIFFERENCES OF MONTHLY IRRADIATION IN % (STCE)

Month	Days	PVGIS -CMSAF	PVGIS -3	Satel- -Light	NASA- -SSE	HC-3
1	62	119.3	130.0	193.2	194.1	123.3
2	56	10.2	24.2	6.7	42.1	-12.4
3	62	10.9	-5.8	-5.6	1.8	-3.5
4	90	18.0	-3.0	-3.1	-6.2	21.4
5	93	7.3	1.6	5.8	-0.7	1.4
6	90	8.0	-2.7	-1.5	-6.9	5.9
7	93	-8.5	-8.7	-18.7	-15.7	-7.0
8	93	3.2	-3.8	-5.6	-7.9	-3.4
9	90	-2.9	-16.5	-14.9	-17.3	16.5
10	93	-13.3	-12.3	-21.5	-26.8	1.0
11	60	17.6	12.7	26.9	19.2	6.2
12	62	-17.9	-37.7	-10.7	-10.3	-48.2

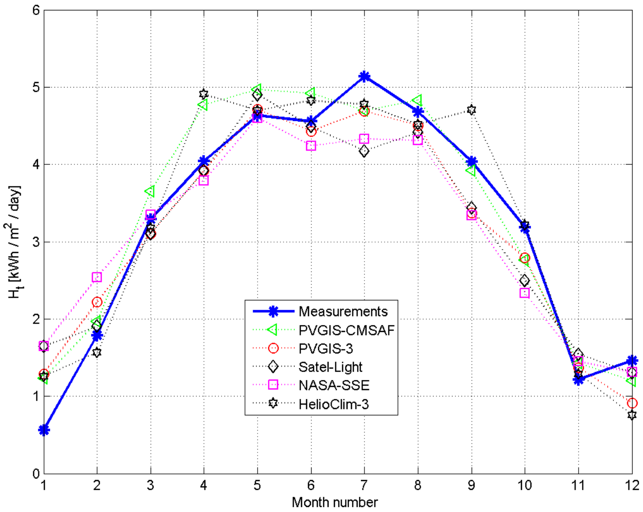

Fig. 4. Measured and estimated average daily irradiation (STCE)

which yields accurate sums of annual irradiation.

V. CONCLUSION

In this paper we have compared monthly global irradiation on a tilted plane delivered from five databases with results of ground measurements from two independent sites located in Poland.

The comparison of tilted-plane irradiation values shows that the forecasts from databases tend to overestimate GTI values in winter and underestimate in summer. This effect can be caused by imperfections of solar radiation decomposition and transposition algorithms. A similar tendency affecting Meteosat-based irradiation estimation during overcast and cloud-free days has been reported in Norway [6]. These discrepancies may be also caused to some extent by different time periods of databases and variations in climate.

Large differences in GTI values during winter may be caused by temporal snow coverage of PV cells. They have substantial impact on the sizing of a stand-alone PV system components as the month with the worst-case solar radiation should be considered in this procedure, according to IEEE Guide for Array and Battery Sizing in Stand-Alone Photovoltaic Systems [21]. This can lead to selection of undersized PV module or battery. As a result, the system will fail when the PV module receives too low value of effective irradiation during time longer than the system's autonomy. In order to avoid this problem, corrections in PV array and battery sizing should be applied. A module with respectively higher power rating should be selected, otherwise the designer should be aware that the stand-alone PV system may be not functional during some time in winter.

Despite different time periods, the variations of GTI estimates are negligible in case of a year's scale. This time both estimated and measured values are in good agreement and the yearly sum of irradiation can be forecasted on the basis of solar radiation databases with 5% accuracy. The same level of mean bias error for global horizontal irradiance has been reported in [10], [11], [5]. Such a precision should be sufficient for performance evaluation of a grid-tied PV system and estimation of annual energy production.

The values of average annual irradiation on inclined surface, obtainted from a web database or from Tab. V, VI, can be used to estimate the total energy generated during a year in a PV module located in the same climate area and based on the same technology. Such an estimation can be essential for the needs of economical forecasts and can be easily performed by multiplying the global irradiation H_{ty} value and the rated power of PV module or array, defined for STC:

$$E_y \approx H_{ty} P_{max} \text{ [Wh].} \qquad (3)$$

In this calculations we assume that the powered system employs MPPT load that adopts to changes of PV module characteristics. Efficiency of further system components, like e.g. power converters and batteries, have to be taken into account in practical situation.

In a similar way, it is also possible to estimate total energy generated during a given month in a PV module. This can be calculated by multiplying the corresponding average daily irradiation H_t value from the web database or from Tab. VII, IX, by a number of days N_d in the month and the rated power of PV module or array:

$$E_m \approx H_t N_d P_{max} \text{ [Wh].} \qquad (4)$$

Uncertainty of such an estimation will be higher, however, than in case of annual energy production forecasts (3).

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