INTERNATIONAL CONFERENCE enviBUILD BUILDINGS AND ENVIRONMENT 2019
STU SvF
7th November, Slovak University of Technology, Bratislava

SOLAR IRRADIANCE AVAILABILITY BASED ON BRATISLAVA MEASUREMENTS

Stanislav Darula[1], Branislav Schnierer[2], Marta Malikova[3]

[1] Institute of Construction and Architecture Slovak Academy of Sciences, 9 Dubravska Road, SK-845 03 Bratislava 45, Slovakia, Email: usarsdar@savba.sk
[2] Solargis Ltd., Milana Marecka 3, 841 07 Bratislava, Slovakia, Email: branislav.schnierer@solargis.com
[3] Institute of Construction and Architecture Slovak Academy of Sciences, 9 Dubravska Road, SK-845 03 Bratislava 45, Slovakia, Email: malikova.marta@savba.sk

ABSTRACT

Climate changes can be observed in last decades evidently. Generally, temperature and sunshine are rising also in countries located in higher geographical latitudes. These facts have impact on the design building constructions and indoor environment. Sun with its direct radiation is basic source of energy on the Earth and has important influence on visual task performance and application of shading devices in building apertures to avoid overheating and glare phenomena. The precise measurements of global, direct and diffuse irradiances are carried out in Bratislava at the Institute of Construction and Architecture Slovak Academy of Sciences with cooperation of Solargis Ltd. Bratislava. These data, after quality control processing, are the basis of the irradiance availability research. Applied methods for data evaluation and determination of for solar irradiance availability are based on the statistical procedures.

Paper presents results of experimental solar irradiance measurements provided in Bratislava, determination of direct solar irradiance availability and discusses importance of solar irradiance availability in point of view of the building environmental quality and building design.

INTRODUCTION

Sun radiation is significant climate component influencing not only indoor environment but also energy performance of buildings in the annual scale [1, 2]. Its availability in the locality is needed to more effective utilize sun radiation during a year.

Buildings should be constructed to respect climate conditions of the locality. This postulate was formulated by Vitruvius one century B.C. [3]. History show us that requirements for access to sun are valid also today. In the antique period climate was more stable as is in present time. Climate changes can be observed last decades more evidently, the temperature is rising, more sunny situations occur and buildings are exposed to more frequent extreme weather situations. Sun radiation is important variable because significantly influences the quality of the indoor environment [4,5]. Sun radiation has positive health effects mainly for children growth and generally is preferred during colder months. On the other hand sun radiation is unacceptable in interiors during warm summer days and in work places because of overheating and glare occurrence [6].

Building interiors are illuminated through vertical, slope or horizontal apertures. To control sun radiation in buildings, the information about its annual occurrence is needed [7]. There are available databases of measured irradiances generally stored as monthly, daily sums or hourly averages at meteorological stations [8].

https://doi.org/10.2478/9788395669699-007

Walkenhorst found that data taken from one minute measurements are sufficient for study of the dynamic irradiance changes [9].

DESCRIPTION OF MEASUREMENTS

There are many meteorological stations equipped by pyranometers offering irradiance data of various quality. Generally, available hourly data cannot represent occurrence of very high irradiance values which are important for design of window shading systems. Several CIE IDMP stations are in operation over the world measuring illuminance and irradiance. One of such station is still active in Bratislava since 1994 [10]. This station is located on the platform at the roof of the Institute of Construction and Architecture Slovak Academy of Sciences. Geographical coordinates of the site are: geographical latitude φ = 48° 10' 10", geographical longitude λ = 17° 04' 17" E while elevation is approximately 185 m above sea level (roof of the building). Solar radiation data used in this study is collected within a collaboration of the Institute of Construction and Architecture, Slovak Academy of Sciences, and Solargis Company.

Global horizontal irradiances $E_{e,g}$ are measured in 1 minute step by the pyranometer Kipp and Zonen CMP 10, Class A, as well as global $E_{e,g}$ and diffuse horizontal irradiances $E_{e,d}$ by the pyranometer Reichert GmbH RSP 4G RSP, Class B, equipped by the rotating shadow band and Li-200 sensor, see Figure 1. Direct normal irradiance was calculated as difference between E_{eg} a E_{ed} measured by RSP 4G, i.e. $E_{es} = E_{eg} - E_{ed}$. In Table 1 there are documented fluency and measurement outflow of measured parameters.

Cupola and diffusor of measurement instruments are regularly cleaned 2 – 3 times per week or more frequently in the case of snowy situations or occurring dirt and per two-week there are common inspections and quarterly there are detailed inspections of the measuring system. All data are recorded in the GMT +1 h time.

Table 1. Database of the measured irradiance at the Institute of Construction and Architecture in Bratislava.

Parameter	Pyranometer	2016	2017	2018			2019
		IX -XII	I-XI	XII	I-III	IV-XII	I-VI
$E_{e,g}$	Kipp & Zonen CMP 10	▨	▨	▨	▨	▨	▨
$E_{e,g}$	RSP - Rotation shadowband pyranometer	▨	▨	Missing data due to calibration of the RSP in Spain		▨	▨
$E_{e,d}$		▨	▨			▨	▨
$E_{e,s}$		▨	▨			▨	▨
Note	▨	Data included in the database					
	$E_{e,g}$ - global horizontal irradiance, $E_{e,s}$ – direct normal irradiance, $E_{e,d}$ – diffuse horizontal irradiance						

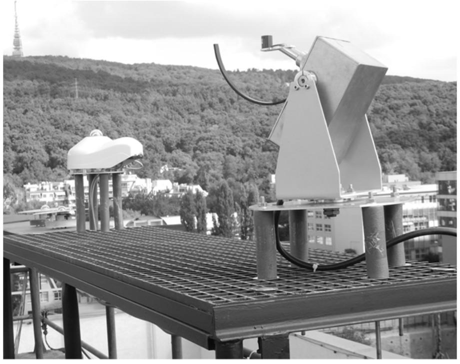

Figure 1. View on the pyranometers at the platform.

QUALITY CONTROL OF MEASURED DATA

The quality control (QC) was performed before the study and analysis of measured data. There are several methods with specific tests to eliminate occurrence of data with extraordinary values and mistakes during measurements. QC tests can cover various tests in dependence on purposes. The recommendations published in document [11] are applied for data processing at the CIE IDMP stations (International Daylight Measurement Programme).

The Quality Control applied in this study is based on the method defined in SERI QC procedures, [12,13]. This QC is generally implemented in the irradiance research. The SERI QC processing consists of two steps:

A. First, the automatic tests are run to identify the obvious issues. Automatic quality control includes:
- Identification of missing values,
- Correction of time shifts,
- Evaluation of measurements against sun position,
- Comparison of data with possible minimum and maximum irradiance limits,
- Evaluation of consistency of $E_{e,g}$, $E_{e,d}$ and $E_{e,s}$ by comparing the redundant measurements.

B. Second, inconsistencies are identified by the visual inspection and marked. Visual quality control aims to identify and mark the following erroneous patterns:
- Shading from nearby objects (near shading) or mountains (far shading),
- Regular data error patterns,
- Irregular anomalies,
- Comparison of data from multiple sensors (if available).

Data which are not passing one or more QC tests were marked and excluded from database for next analysis.

METHODOLOGY AND RESULTS

New EN 17037 published in December 2018, introduces also criteria for evaluation of daylight and glare in building interiors. The energy performance of buildings is evaluated after standard [1] by a method considering also annual effects of the sun radiation. The direct sun radiation is applied in both standards but more precise in building design data are missing.

Locality in Bratislava represents central European climate with four specific seasons: winter, spring, summer and autumn. The sun radiation penetrated into rooms can improve thermal indoor comfort and energy balances during spring or autumn seasons but higher levels are risky because of overheating and glare occurrence. This was reason for study also monthly statistics of direct irradiance availability.

There are several possibilities for determination of sun radiation availability in a locality. Monthly, daily or hourly averages of sun irradiance are often inputs into energy simulation of the energy consumption in buildings. Instantaneous data allows to study dynamic changes of sun radiation and limits of occurred values. New standard [6] introduces for daylight evaluation in building interiors a climatic statistical parameter based on the annual availability of the diffuse illuminance. Because interiors are exposed also by sun radiation during significant time in a day one can expect that similar concept will be used for determination of availability of solar irradiance.

This study is based on the one minute regular measurements carried out in the Bratislava. Data obtained from the period 2016 – 2019 were processed against Data Quality Control tests [12,13] to collect high quality database. Only sunny situations are considered. Because buildings are generally occupied by users more than 40 % of the performance time, the percentiles representing more than 40 % occurrence of E_{es} were searched. Sun radiation conditions change day to day and month to month in dependence on weather conditions and seasonal significance can be observed. Direct normal irradiance availability was also studied in annual period (January to December) and in winter (December, January and February), spring (March, April, May), summer (June, July, August) and autumn (September, October, November) seasons. Parameter percentile reflects also importance of exposition building envelope by sun radiation of various intensity during a year. The probability in % when E_{es} is exceeded in winter time is plotted in Figure 2. Obtained percentiles are documented for winter season in Table 2. The effect of sunshine can be tested by the condition when E_{es} is at least 120 W/m^2 [11]. It can be concluded from Table 1 that such situations occur for more than 70 % sunny winter time.

Also, high differences between E_{es} statistics of individual years can be observed. For example, percentile $K^{(70)}_{2016\text{-}2017}$ = 222,5 W/m^2 is 2,1 times higher than $K^{(70)}_{2018\text{-}2019}$ = 105,0 W/m^2. The later winter is characterized by less sunshine because E_{es} = 105,0 W/m^2 is lower than 120 W/m^2. The risk of glare was noticed only for duration of 60% of sunny situations in winter 2018 - 2019.

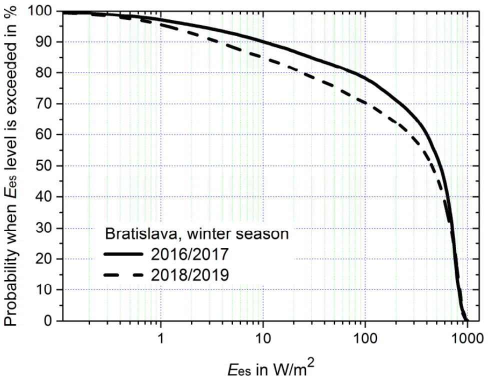

Figure 2. Occurrence of direct horizontal irradiance in winter season.

Table 2. Percentiles of E_{es}, winter season.

Period	Percentile, [W/m^2]				
	40	50	60	70	80
2016-2017	641.6	541.5	401.3	222.5	76.1
2018-2019	580.6	449.0	275.0	105.0	24.3
Winters in 2016-2019	614.5	499.3	346.5	161.5	42.4

The percentiles for spring season were determined by the similar way. Achieved results are documented in Table 3 and plotted in Figure 3. The effect of higher sun positions during spring is evident in higher E_{es} levels. Duration of spring sunshine is longer up to 80% of the time of sunny situations.

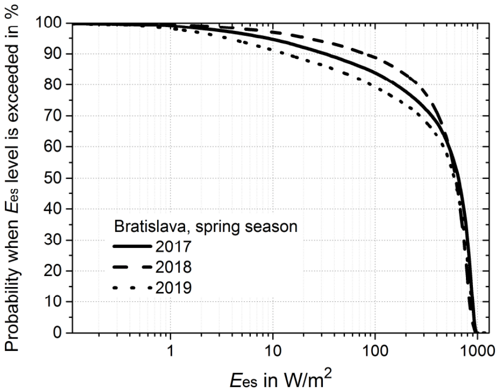

Figure 3. Occurrence of direct horizontal irradiance in spring season.

Table 3. Percentiles of E_{es}, spring season.

Period	Percentile, [W/m^2]				
	40	50	60	70	80
2017	736.3	653.4	526.2	358.3	159.6
2018	678.7	613.3	528.6	415.5	262.4
2019	685.5	593.8	465.4	275.2	90.3
Springs in 2017-2019	702.0	620.4	508.5	351.9	157.0

The highest values of E_{es} was found in summer season. Glare in interiors can occur for more than 80 % sunny summer situations, Table 4 and Figure 4. Interesting results conclude from comparison spring and autumn seasons, Table 3 and Table 5. The E_{es} values when are exceeded are plotted in Figure 5.

As higher E_{es} values were investigated the lower differences between seasons were found, see Table 2 - Table 5. Values of 40th percentile $r^{(40)}_{winter}$ = 614,5 W/m^2, $r^{(40)}_{spring}$ = 702,0 W/m^2, $r^{(40)}_{summer}$ = 694,8 W/m^2 and $r^{(40)}_{autumn}$ = 650,2 W/m^2 differ from average 2,3 % - 7,6 %.

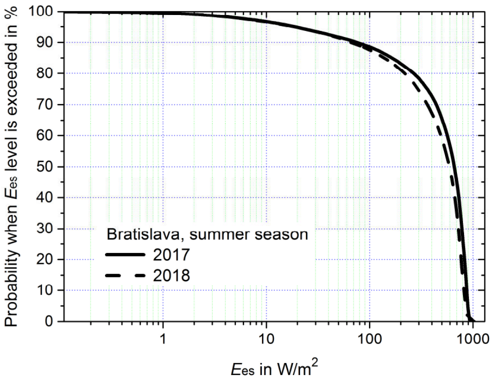

Figure 4. Occurrence of direct horizontal irradiance in summer season.

Table 4. Percentiles of E_{es}, summer season.

Period	Percentile, [W/m^2]				
	40	50	60	70	80
2017	731.7	661.2	565.8	444.0	267.0
2018	667.6	593.0	489.9	363.2	218.6
Summers in 2017-2018	694.8	622.9	523.0	396.5	236.6

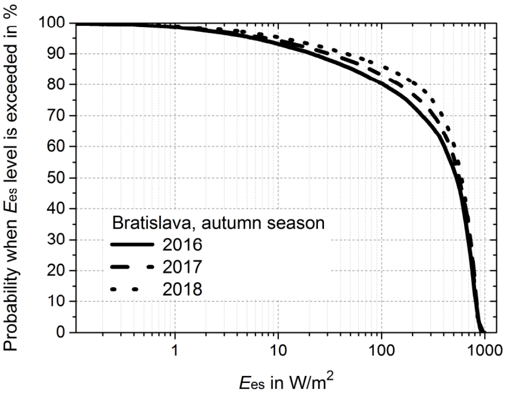

Figure 5. Occurrence of direct horizontal irradiance in autumn season.

Table 5. Percentiles of E_{es}, autumn season.

Season	Percentile, [W/m^2]				
	40	50	60	70	80
2016	622.2	534.1	405.5	247.7	104.6
2017	653.2	564.2	458.7	323.1	148.9
2018	665.3	593.2	508.0	387.5	217.3
Autumns in 2016-2018	650.2	570.2	467.3	331.6	157.6

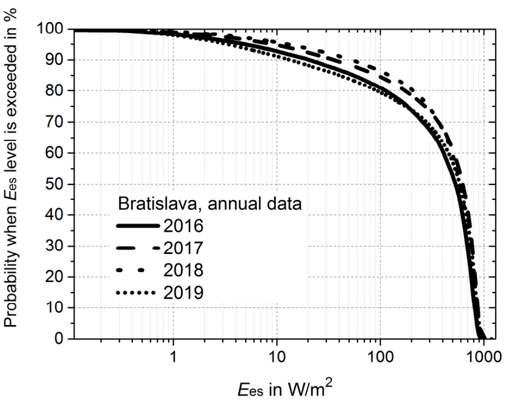

Figure 6. Occurrence of annual direct horizontal irradiance.

Table 6. Percentiles of the annual direct horizontal irradiance E_{es}.

Period	Percentile, [W/m^2]				
	40	50	60	70	80
2016	622.7	534.2	409.4	258.3	112.7
2017	710.7	629.2	517.1	368.4	176.0
2018	666.1	592.4	495.6	370.1	210.8
2019	677.9	585.1	458.5	280.1	93.4
Years 2016-2019	680.4	598.9	491.1	258.3	166.3
Annual difference between maximum and minimum	88	95	86.2	111.8	117.4

Evaluation of annual occurrence E_{es} values shows decreasing trend of differences with increasing E_{es} value, Table 6. Variation of E_{es} within percentile follows the same trend. The closest seasonal percentile values to annual were found in autumns $r^{(80)} = 157.6$ W/m^2, $r^{(70)} = 331.6$ W/m^2, $r^{(60)} = 331.6$ W/m^2, in summer median $r^{(50)} = 622.9$ W/m^2 and $r^{(40|} = 694.8$ W/m^2, see Table 7.

Table 7. Comparison of seasonal and annual percentiles direct horizontal irradiance E_{es}.

Period	Percentile, [W/m^2]				
	40	50	60	70	80
Winters in 2016 - 2019	614.5	499.3	346.5	161.5	42.4
Springs in 2017 - 2019	702.0	620.4	508.5	351.9	157.0
Summers in 2017 - 2018	694.8	622.9	523.0	396.5	236.6
Autumns in 2016 - 2018	650.2	570.2	467.3	331.6	157.6
Years 2016 - 2019	680.4	598.9	491.1	258.3	166.3

VARIABILITY OF DIRECT HORIZONTAL IRRADIANCE

The direct irradiance variability was investigated by the statistic IQR - Interquartile Range (1), [14]. If IQR value is high, then also variability of measured data is high while two parameters H_1 and H_2 were tested. If value H_1 is lower than $E_{es} = 0$ or H_2 is higher than maximum E_{es} then the occurrence of the direct normal irradiance is characterized by high variability. General formula for IQR calculation is:

$$IQR = Q_3 - Q_1 \qquad (1)$$

in the case of inversion E_{es} distribution is valid

$$IQR = Q_1^{(75)} - Q_3^{(25)} \qquad (2)$$

and parameters H_1 and H_2 can be calculated as

$$H_1 = Q_1^{(75)} - 1.5\ IQR \qquad \text{and } H_2 = Q_3^{(25)} + 1.5\ IQR \tag{3}$$

In Table 7 are documented results of the variability evaluation separately for winter, spring, summer and autumn seasons as well as for annual periods. The high variability of E_{es} is noticed for all seasons with different $H_2 - H_1$ range. The simple indicator of variability rate *VR* (4) was proposed to study dynamic conditions of sunny situations. The highest variability was found in winter 2018 - 2019 (*VR* = 0.357) while the lowest variability was calculated for summer 2017 (*VR* = 0.580).

$$VR = \max E_{es}/(H_2 - H_1) \tag{4}$$

Table 7. Evaluation of annual and seasonal E_{es} variability.

Period	**Percentile, [W/m^2]$^-$**		***IQR***	***H1***	***H2***	**Maximum**	**Evaluation**
	25	**75**	**[W/m^2]**	**[W/m^2]**	**[W/m^2]**	**[W/m^2]**	
Winter							
2016 - 2017	738.1	141.1	597.0	-754.4	1633.7	1011.2	High variability
2018 - 2019	732.4	52.8	679.6	-966.5	1751.8	971.6	
Winters 2016 - 2019	736.4	92.2	644.1	-874.0	1702.6	1011.2	
Spring							
2017	827.3	254.4	572.8	-604.9	1686.5	1013.7	High variability
2018	760.9	345.5	415.4	-277.6	1384.1	957.1	
2019	790.7	169.5	621.2	-762.3	1722.4	1186.2	
Springs 2017 - 2019	775.5	226.8	548.7	-596.4	1598.6	1186.2	
Summer							
2017	805.8	361.7	444.1	-304.5	1471.9	1030.8	High variability
2018	746.1	293.6	452.5	-385.1	1424.8	1020.3	
Summers 2017 – 2018	772.8	319.7	453.1	-360.0	1452.4	1030.8	
Autumn							
2016	726.8	175.9	550.9	-650.5	1553.2	976.9	High variability
2017	755.3	235.0	520.3	-545.5	1535.8	968.2	
2018	746.7	311.2	435.5	-342.1	1400.0	993.9	
Autumns 2016 - 2018	744.5	245.6	498.9	-502.7	1492.8	993.9	
Annual							
2016	727.1	183.1	543.9	-632.8	1543.0	976.9	High variability
2017	797.0	274.1	522.9	-510.3	1581.4	1030.8	
2018	748.3	295.3	452.9	-384.1	1427.7	1020.3	
2019	783.3	177.0	606.2	-732.3	1692.6	1186.2	
Years 2016 - 2019	770.9	258.8	512.2	-509.5	1539.2	1186.2	

Table 8. Summary of the variability rate *VR*.

Winter		**Spring**		**Summer**		**Autumn**		**Annual**	
Period	***VR***	**Period**	***VR***	**Period**	***VR***	**Period**	***VR***	**Period**	***VR***
						2016	0.443	2016	0.449
2016 - 2017	0.423	2017	0.442	2017	0.580	2017	0.465	2017	0.493
		2018	0.576	2018	0.564	2018	0.570	2018	0.563
2018 - 2019	0.357	2019	0.477					2019	0.489
Winters	0.392	Springs	0.540	Summers	0.569	Autumns	0.498	Years	0.579

CONCLUSIONS

Levels of sun radiation on the ground continually change since sunrise to sunset due to various sun position on the sky, cloudiness and turbidity of atmosphere. This facts significantly influences availability of direct normal irradiance levels. To design effective utilization of workplaces in building interiors during a year, it is important to have information also about occurrence sun radiation which can cause overheating and glare. In accordance to [11] presence of sunshine can be registered when $E_{es} > 120$ W/m^2. Such situations with risk of glare occurrence were found out in 80% of sunny cases in the investigated period, Table 7. Findings also give information that also during winter season cases with glare risk can occur during 70 % of sunny situations.
The standard [6] applies expected high illuminance on the eye for evaluation of glare. Value of this critical values is not determined. Presented study offers not only seasonal but also annual E_{es} levels occurring percentage time in a year.

ACKNOWLEDGEMENT

This work was supported by Research Agency of The Ministry of Education, Science, Research and Sport of the Slovak Republic research grant VEGA 02/0042/17 and IEA SHC Task 61.

REFERENCES

[1] EN 15193. (2017): Energy performance of buildings - Energy requirements for Lighting. Brussels: CEN, October 2017.

[2] M. Knoop (Ed.) (2016): Daylighting and Electric Lighting Retrofit solutions. A source book of IEA SHC Task50 'Advanced lighting for retrofit buildings'. Berlin: Universitatsverlag der TU Berlin.

[3] M.P. Vitruvius (1960), *The Ten Books on Architecture*. (English translation by Morgan, M.H.), New York: Dover Public., 1914, 1960.

[4] P. Hykš, J. Hraška (1990), *Slnečné žiarenie a budovy*. Bratislava: ALFA.

[5] T. Muneer (2004), *Solar Radiation and Daylight Models: For the Energy Efficient Design of Buildings*. Oxford: Butterworth-Heinemann.

[6] EN 17037. (2018): Daylight in Buildings. Brussels: CEN, December 2018.

[7] Ch. Chauliaguet, P. Baratsabal, J.P. Batellier (1977), *Solar energy in buildings*. Chichester: Jonn Wiley & Sons Ltd.

[8] V. Badescu (Ed.). (2008): *Modeling solar radiation at the Earth surface*. Berlin: Springer Verlag.

[9] Walkenhorst, O., Luther, J., Reinhart, Ch., Timmer, J. (2004): Dynamic annual daylight simulations based on one-hour and one- minute means of irradiance data. Solar Energy **72**, 5/2004, pg.385-395.

[10] IEA-SHCP-17E-2. (1994): Broad-band visible radiation data acquisition and analysis. A technical report of task 17: Measuring and modelling spectral radiation affecting solar systems and buildings. Vol. 2: Satellite Report No. 1 World Network of Daylight Measuring Stations (IDMP), ASRC Albany, N.Y., August 1994.

[11] CIE 108:1994. (1994): Guide to recommended practice of daylight measurement. Technical Report. Vienna: CIE Central Bureau.

[12] NREL (1993): User's Manual for SERI_QC Software-Assessing the Quality of Solar Radiation Data. NREL/TP-463-5608. Golden, CO: National Renewable Energy Laboratory.

[13] Younes, S., Claywell, R., Muneer, T. (2005): Quality control of solar radiation data: Present status and proposed new approaches. Solar Energy **30**, 9/2005, pg.1533-1549.

[14] L. Sachs (1982), *Applied statistics. A handbook of techniques*. New York: Springer - Verlag.