Analysis of Daylight Availability in Italy trough different Luminous Efficacy Models

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Abstract

This paper presents the results of a study aimed at developing an Italian database of Typical Meteorological Year (TMY) for the global and diffuse outdoor illuminance, starting from solar irradiation measurements and luminous efficacy models. The main objective is to provide reliable climatic data to be used for the estimation of the daylight availability in buildings and predict the energy requirements for electric lighting with higher accuracy than the actual relevant standard. ENEA developed the national solar radiation atlas during the past years, implementing validated models to predict the global, direct and diffuse irradiation, starting from satellite remote sensing. For this study, the most relevant luminous efficacy models were applied to develop illuminance TMY starting from solar irradiation data. Illuminance availability curves were developed for three reference localities of the Italian territory (Milan, Rome, Palermo), highlighting how results can be used to derive the potential contribution of daylight for buildings energy applications. In order to verify the results obtained, a ground measurements compaign of the outdoor illuminance, was started to test the effectiveness of model. The first data processed, show low differences between estimated values and measured data, confirming the validity of selected model.

Keywords: Daylight availability; luminous efficacy; outdoor illuminance, TMY,

1. Introduction

The building sector is responsible for more than 40% of the energy end uses in Europe and plays a relevant role to reach the environmental and energy targets, in national and European policies [1,2,3]. It is also recognized that the energy performances of building should be addressed to the whole energy services, and not only the space heating as happened in the past decades [4]. Relevant studies carried out during the past years demonstrated the impact of the electric lighting on the energy uses in buildings. The figures are particularly relevant for the not residential buildings: 14% of the total consumption in EU, 26% in USA [5,6]. A study carried out recently in Spain set in 31% the share of the electricity uses on the total final demand in commercial buildings [7]. As a consequence, the energy savings in this energy service are found to be highly competitive in technical and economical perspective [8]. A relevant potential hence exist to improve the performance of existing and new building in terms of lighting energy uses.

It has to be noted that potential energy savings are often estimated in terms of higher efficiency of the electrical devices (lamps, luminaries, control sensors and systems) more than exploiting the daylighting potentialities by the implementation of advanced strategy and solutions. The reference document in EU for the assessment of lighting requirements in building is the EN standard Energy performance of Buildings. Energy requirements for lighting, which provides an operational method and two calculation methods, different in accuracy and complexity [9]. However, the reliability of the prediction methods needs to be carefully addressed, since the over/underestimation of the consumption respect to the practice is an obstacle to the technology spread, especially in the nearly zero energy building (nZEB) vision.

A critical issue is the assessment of the daylight contribution, which does not take into account the climatic conditions of the investigated locality. The Daylight Autonomy concept emerged in the past years as relevant metric to assess the daylighting contribution and, as a consequence, potential energy savings that can be achieved in buildings for the electric lighting service [10, 11]. Climate based approaches are getting interest for

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daylighting design methods, as described in [12]. The approach is also adopted in the implementation of an Italian alternative method is currently on going [13], whose main objective is merging the climate based daylighting with the calculation flux defined in [9].

The alternative method evidences the importance of robust and reliable climatic data, in this case global, direct and diffuse illuminance. This paper presents the first results of a review work aimed at developing an national atlas for outdoor illuminance data for building applications.

2. Objective and method

ENEA has defined an extensive database of hourly values of radiometric quantities: global horizontal irradiance (Igh), diffuse horizontal irradiance (Idh) and Direct Normal Irradiance (Idn) for any Italian site, have been derived by processing satellite data [14,15,16,17] provided by the EUMETSAT [18]. Advantages of satellite based data respect to ground measurements mainly depend of the fact that the latter are taken on a limited number of stations, while the former can be derived, if accurately geo-referenced, for any locality on the earth surface. Satellite images provide a measure of the reflection coefficient (albedo) of the planet surface at the switch instant. The algorithms developed by ENEA, based on the original idea of D. Cano et al. [19], compare the actual albedo with a reference one and convert the difference into a clearness index, used to derive the Igh. The application of additional empirical models of the atmosphere [20,21] allows to split Igh in its components: direct and diffuse. The results of the zoning of the solar radiation in Italy are published in the solar radiation atlas published by ENEA [14], which is going to be updated so to cover a 10 years observation period (2006-2015).

Core of this study is the use of radiometric quantities to derive correspondent photometric quantities, in order to build illuminance typical reference years to be used to assess the lighting performance of buildings. It has to be noted that radiometric and the photometric quantities are closely related, as the former measure the energy and the power of electromagnetic radiations, while latter translate the same energy or power in terms of visible light, linked to the physiological ability of the human eye. Since very few data, based either on ground or satellite measurements, are available to build illuminance reference years, empirical models were implemented. These models express the luminous efficacy of the solar radiation (ratio of the illuminance on the irradiance) as a function of variables that describe the sky conditions and the and the solar zenithal angle θz, clearness index KT, diffuse to global radiation ratio k, "clearness" and/or "brightness" indexes. Non general models, as those not implementing all the radiation components or those implemented for specific orientations, were not taken into account. In the this study some of most relevant models were taken into account and from in [22,23,24,25,26,27]. From now on selected models will be identified by the main author of the above listed references.

- Cucumo model, calibrated by irradiance and illuminance measurements at Arcavacata di Rende (CS), Italy [22].It is the simplest model of correlation, based on the direct proportionality between outdoor illuminance and irradiances.
- Muneer model, based in measurements taken in five UK localities, taken in the last decade of the previous century [23]. It is a
- relatively simple model that doesn’t consider the current position of the sun and assumes the luminous efficacy expressed by polynomial equation linked to the only global transmission and the poliynomial coefficients derived by statistical regression.
- Perez model. Based on measurements taken in 10 USA and 3 European localities for periods ranging from few months up to 3 years. The model takes into account also the atmospheric precipitable water or, alternatively, the dew point temperature [24]. The irradiance not directly appear in the model expressions, but are combined with extra atmospheric irradiance, in specific indices: Perez's sky clearness index and Perez sky's brightness index. The model also takes into account the position of the sun through the zenithal angle. In the Perez simplified model, the hourly data of dew points are replaced with a daily mean value, constant for all the year. This simplification was introduced to test the impact of the parameter on the model accuracy, being often the dew point data of difficult availability

- Robledo models, based on historical series of data measured in 1994/95 in Madrid, Spain [25,26,27].

The Robledo and Soler models are as accurate as the Perez one, since they take into account the sun position and the sky's brightness and, at the same time, they only need few coefficients. Several models were developed as a function of different sky conditions: clear sky, partly cloudy and overcast sky. Furthermore simplified models are available to consider any weather conditions.

Outdoor illuminance time series database were thus built starting from an extensive solar irradiation time series database and luminous efficacy models. The time series were, next, used to develop a hourly based TMY (Typical Meteorological Year). The adopted criteria was to select, for each month of the year, a real complete month, among those available in the multi-year series, which best fitted the average of the multi-year datasets related to the specific month. This approach allows keeping the average values on the long term and catching the short term variability of the analyzed quantity, as it takes place in the reality. Reference months were selected using GHI as driving parameter, being the quantity directly derived from the satellite image.

TMYs were implemented for the following quantities: global horizontal (Egh), diffuse horizontal (Edh) and direct-normal illuminance (Edn), as done in the past for the solar irradiation. The TMY were developed for three reference localities:

- Milan, latitude 45°N, climatic conditions characteristics of the northern Italian regions.
- Rome, Latitude 41°N, climatic conditions characteristics of the central Italian regions.
- Palermo, 38°N, climatic conditions characteristics of the southern Italian regions.

This preliminary exercise has also the objective of model calibration and/or adjustment by comparison with ground measured data as next step. A total of 15 TMYs was developed, including 3 localities and 5 different luminous efficacy models, having introduced a sensitivity test on water content in model [22]. The TMYs, implemented with the different models, were compared to assess coherence among them and their suitability in providing reliable data to predict energy requirement for lighting in buildings.

The comparisons were made for all models, with reference to the three locations and two lighting quantities (global and diffuse illuminance). The diagrams analyses and the approach indices show minimal differences of each model compared to any other. It is worth noting that for each model a very good agreement was found for the global luminous efficacy, while higher discrepancies were found for the diffuse luminous efficacy. This topic, which needs deeper analyses, might be related to selective phenomena related to the spectral distribution of the solar radiation under variable sky conditions

3. Calculation

Once the TMYs were developed, calculations were carried out to check and compare the different luminous efficacy models. A preliminary check was carried out for the Perez model, with the objective of quantify the impact of the simplification introduced in the previous section. The TMYs of the three localities for the simplified Perez model were implemented taking into account a constant dew point temperature Td (10.3 °C for Rome, 9.4 °C for Milan, 11.4 °C for Palermo). Relevant statistical parameters were calculated to quantify this assumption, namely: the Bias (or Mean Bias Error, MBE), the Mean Bias Error Percent (MBE%) and Root Mean Squared Error Percent (RMSE%), defined as follow:

$$MBE\% = \frac{MBE}{Mean\ of\ observations} x100 \qquad RMSE\% = \frac{RMSE}{Mean\ of\ observations} x100$$

in this case the "*observations*" are the Perez standard model values, considered as benchmark.

Calculation were carried out for the three localities, as an example for Rome (Tab. 1). It resulted: MBE = -155 lx; MBE% = –0.4 % e RMSE% = 1.3 %. The test was carried out for Rome also using extreme dew point values (Tab. 2), -13 °C and +22 °C. Negligible differences were found, in relation to the accuracy required for the purpose of the study.

Tab. 1: Comparisons simplified (max, min and average dew point) and standard Perez model. City: Rome

Model	Illum.	MBE [lx]	MBE %	RMSE [lx]	RMSE %	Mean [lx]
Perez with Dew point average = 10.3 °C	Global	-155	-0.4	531	1.3	42410
	Diffuse	-52	-0.3	297	1.8	16645
	Direct	-33	-0.1	627	1.5	40889
Perez with Dew point min = –13.3 °C	Global	-928	-2.2	1444	3.4	42410
	Diffuse	-519	-3.1	770	4.6	16645
	Direct	938	1.0	1608	3.9	40889
Perez with Dew point max = 22 °C	Global	1062	2.5	1529	3.6	42410
	Diffuse	683	4.1	970	5.8	16645
	Direct	-724	-1.8	2051	5.0	40889

Tab. 2 : Comparisons of simplified (average Dew Point) Perez model for different cities

Model	Illum.	MBE [lx]	MBE %	RMSE [lx]	RMSE %	Mean [lx]
Milan Perez with Dew point average = 9.4 °C	Global	-223	-0.6	601	1.6	37657
	Diffuse	-136	-0.8	397	2.5	16151
	Direct	87	0.3	762	2.2	34525
Rome Perez with Dew point average = 10.3 °C	Global	-155	-0.4	531	1.3	42410
	Diffuse	-52	-0.3	297	1.8	16645
	Direct	-33	-0.1	627	1.5	40889
Palermo Perez with Dew point average = 11.4 °C	Global	-175	-0.4	618	1.4	45653
	Diffuse	-77	-0.4	373	2.1	17963
	Direct	19	0.0	745	1.8	41779

According to the above tables it can be inferred the slight impact of the hourly dew point data on the final form of the luminous efficacy model, thus the simplified model was selected for the final comparison. Each model was compared versus the other three ones in the next step. An example is provided in figure 1, where a graphical comparison between two models is promptly achieved by scatter plots.

According to the approach index calculated for all the comparisons, it was found that differences among models are small. The calculation exercise led to the final decision of applying the Robledo model to build the Italian TMY illuminance database. In table 3 the comparison of the TMYs built using Robledo versus the TMYs based on the other model is presents by means of relevant statistic indicators

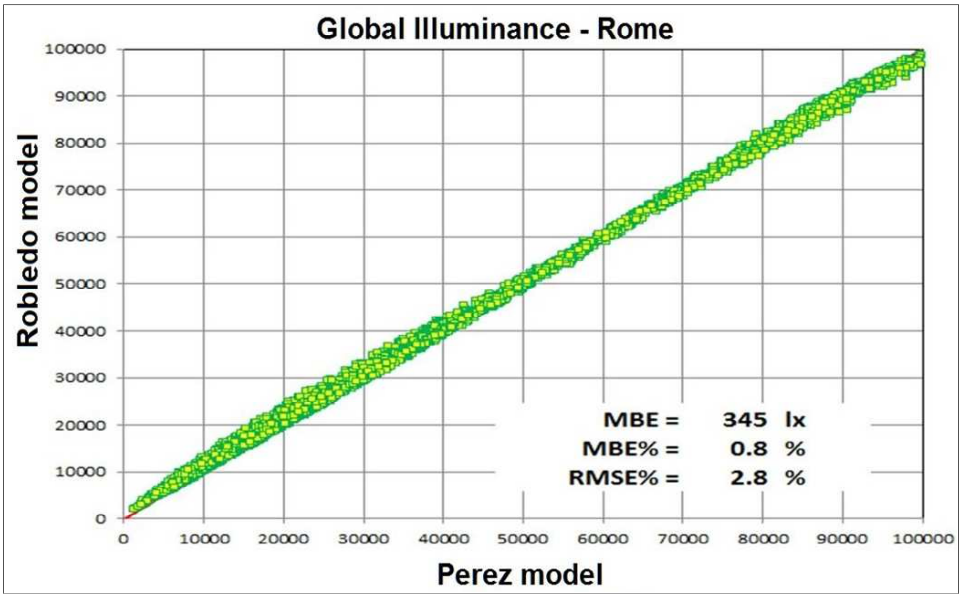

Fig. 1 Global illuminance values (Egh, in lx) of a typical year -town of Rome -comparison between two models

Tab.3 Comparisons with the Robledo model. City Rome

Model	Illum.	MBE [lx]	MBE %	RMSE [lx]	RMSE %	Mean [lx]
Perez standard	Global	-345	-0.8	1183	2.8	42770
	Diffuse	-1052	-5.9	1811	10.2	17700
	Direct	788	2.0	2192	5.5	40115
Perez with Dew point average = 10.3 °C	Global	-500	-1.2	1095	2.6	42770
	Diffuse	-1104	-6.2	1830	10.3	17700
	Direct	755	1.9	1965	4.9	40115
Cucumo	Global	-492	-1.2	1348	3.2	42770
	Diffuse	-3117	-17.6	3540	20.0	17700
	Direct	5007	12.5	5878	14.4	40115
Muneer	Global	1295	3.0	2160	5.0	42770
	Diffuse	-1606	-9.1	2143	12.1	17700
	Direct	4989	12.4	6380	15.9	40115

The Robledo model takes into account the sun position and the sky brightness, factors influencing the luminous efficacy, however the model is expressed in a compact form and do not takes into account the dew point temperature, figure of difficult availability. The Robledo model, here reported for clarity, is based upon the following equation set [25,26,27] :

$$\begin{cases} \eta_{dh} = \left(91.07 \cdot \Delta^{-0.254}\right)\ lm\ W^{-1} \\ \eta_{bn} = \left(134.27 \cdot \left(\cos \vartheta_z\right)^{0.269} \cdot \exp\left(-0.0045 \cdot \left(90° - \vartheta_z\right)\right) \cdot \left(1.045 - 0.427 \cdot \Delta\right)\right)\ lm\ W^{-1} \\ \eta_{gh} = \eta_{bn}\left(1-k\right) + \eta_{dh} k \end{cases} \quad \text{(eq. 1)}$$

Where:

η luminous efficacy;
θz zenith angle
Δ sky brightness index:
dh diffuse horizontal
bn direct normal
gh global horizontal

4. Results and Applications

The results following presented refer to the TMYs implementing the Robledo model. Figure 2 and 3 present the results of irradiance and illuminance availability for the global and diffuse quantities. The curves refer to the city of Rome, selected as exemplary locality for brevity, nevertheless similar results were found for Palermo and Milano. The radiometric and photometric quantities are expressed in relative figure (%) respect to the peak value to get rid of the different units and compare the profiles on the same graph.

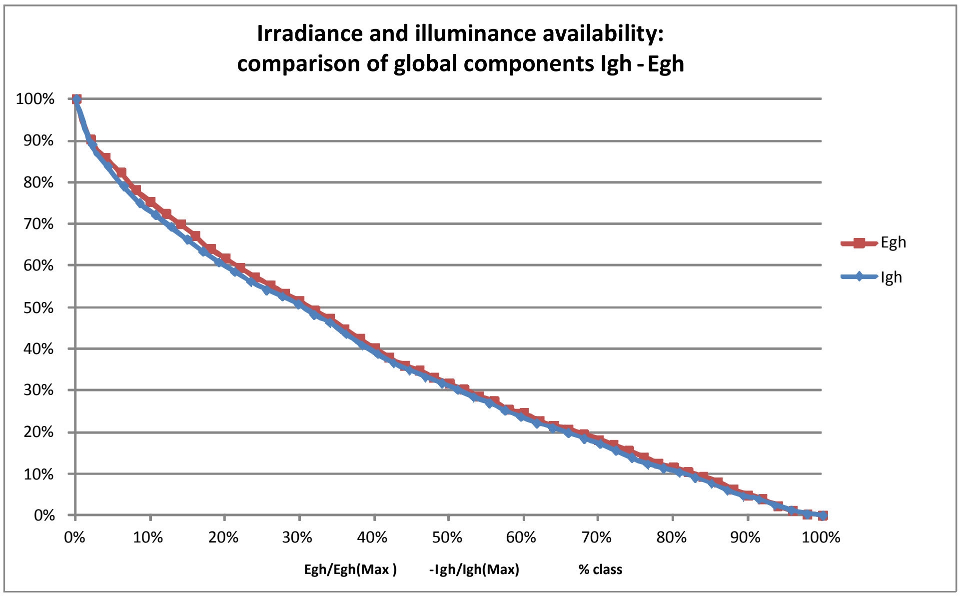

Fig. 2. Comparison of global irradiance Igh and global illuminance Egh

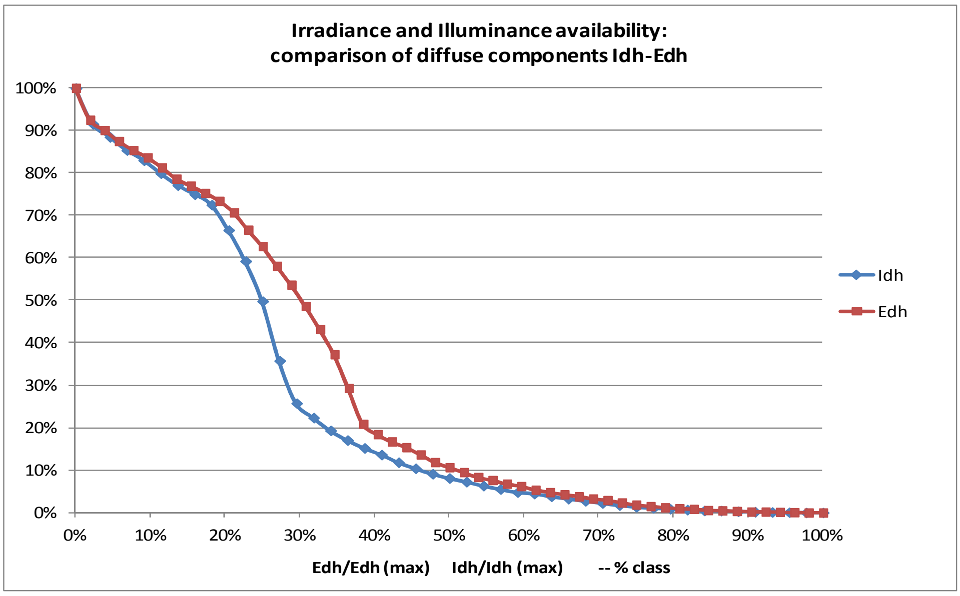

Fig. 3. Comparison of diffuse irradiance Idh and diffuse illuminance Edh

It is interesting to note that global quantities show similar trends, conversely corresponding diffuse components present a different behavior: trends are similar at high and very low relative values, but they show a significant deviation between 20% and 40% of such values.

This behavior evidences luminous efficacy variations, which needs further investigation. At the present stage, it can be noted that the luminous efficacy models takes into account the total solar irradiation, without considering changes in the spectral distribution arising from different sky conditions. Since daylighting metrics use the diffuse illuminance as driving climatic parameter, the latter is following used to present some results potentially relevant for building applications. Figure 3 presents an application of the implemented TMYs: the diffuse illuminance availability in the three reference localities considering the hours from dawn to dusk.

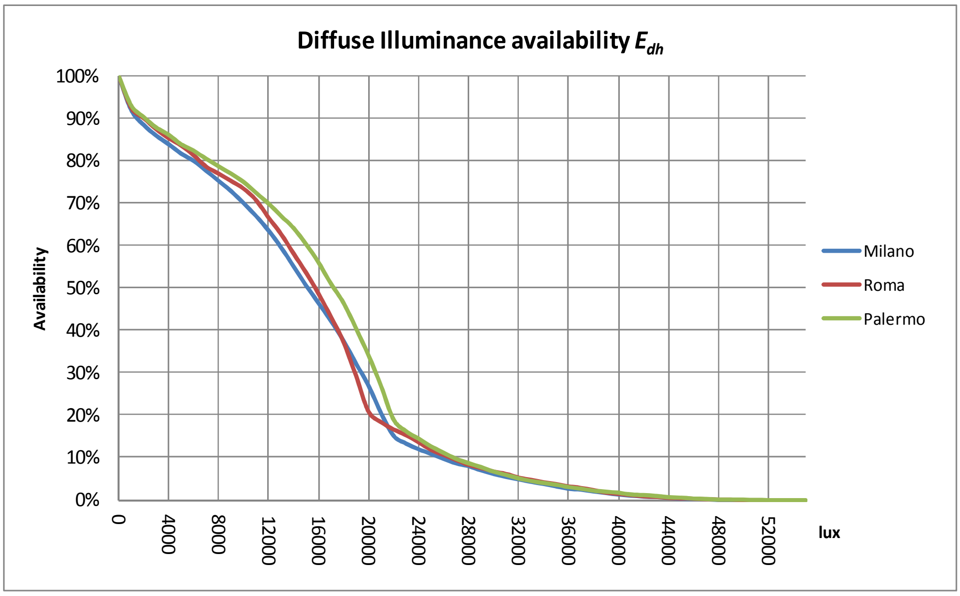

Fig. 4. Diffuse Illuminance availability MI-RM-PA -dawn to dusk-

As expected due its lower latitude, Palermo, have the greater outdoor illuminance availability. The latitude, on the other side, does not explain the result achieved for Rome and Milan. The two curves are very close, despite a latitude difference of about 4°, intersections at about 18000 and 21000 lux. This behaviour, which has a typical summer occurrence, is mainly due to the other higher water and aerosol content in the Milan region, which increases the diffuse components of the solar irradiation respect to the direct one.

Other operative results, derived by the illuminance TMYs, are presented in figures 4 and 5. The former presents the monthly mean diffuse illuminance for the three selected zones, these results are useful to analyze the seasonal variations of the daylight availability and address lighting solution for new and existing buildings, once operation times (8-18 in the example in figure) and indoor visual tasks are defined. Figure 5 presents possible manipulations of the TMYs to provide data tailored to the building needs. The two plots report the diffuse illuminance availability for the case of Rome for two different time usage: from dawn to dusk and for the 08:00-16:00 schedule, which is typical as an example for Italian schools. Holidays and festivities are excluded in the working hours count.

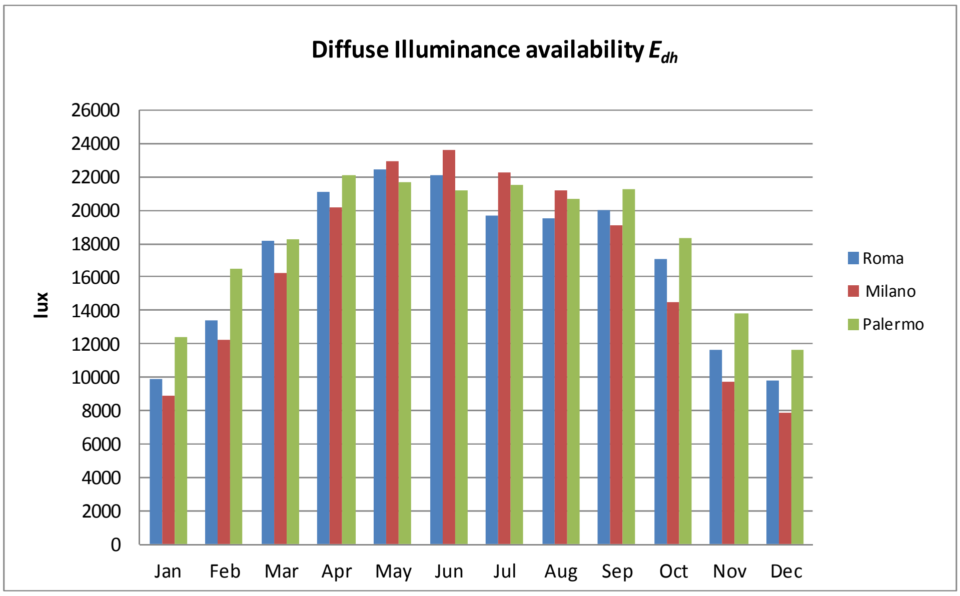

Fig. 5. Edh monthly average values MI-RM-PA operating time 8-18

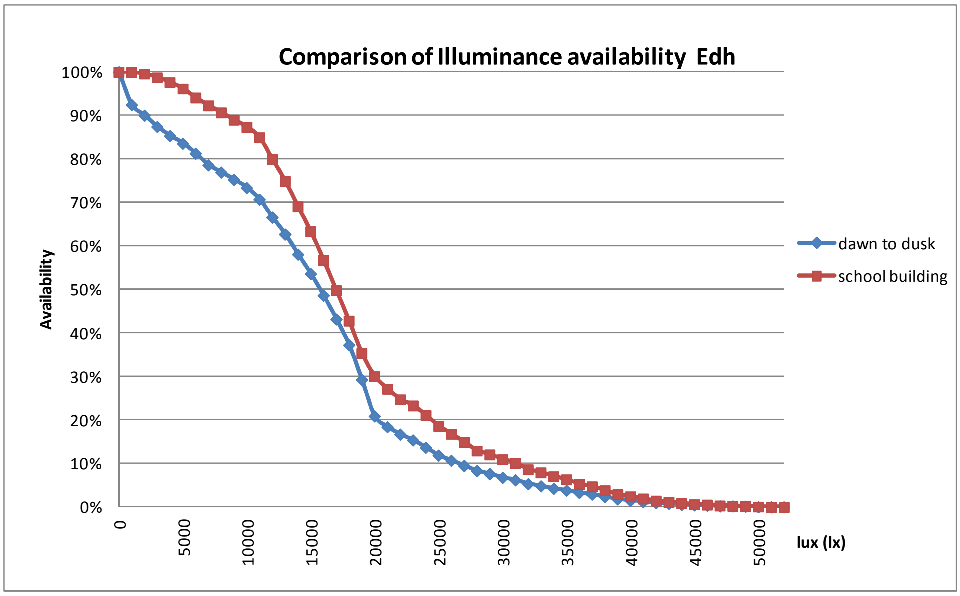

Fig. 5. Edh availability in Rome. Comparison: dawn to dusk and school building with operating time 8-16

5. Validation of model

In order to verify the results obtained, a ground measurements campaign was started in three different Italian sites, Milan, Rome and Lampedusa, to test the effectiveness of model, taking into account different latitudes of Italian territory (Tab 4). The scatter plots are reported figs. 6-7

Tab. 4: Measurements station sites

Site	Coordinates	Measurement [lx]	Sampling time [s]
Lampedusa island	35° 30.0' N 12° 36.5' E	Egh	10
Rome	42° 02.5' N 12° 18.4' E	Egh, Edh	10
Milan	45° 27.9' N 9° 11.3' E	Egh, Edh	10

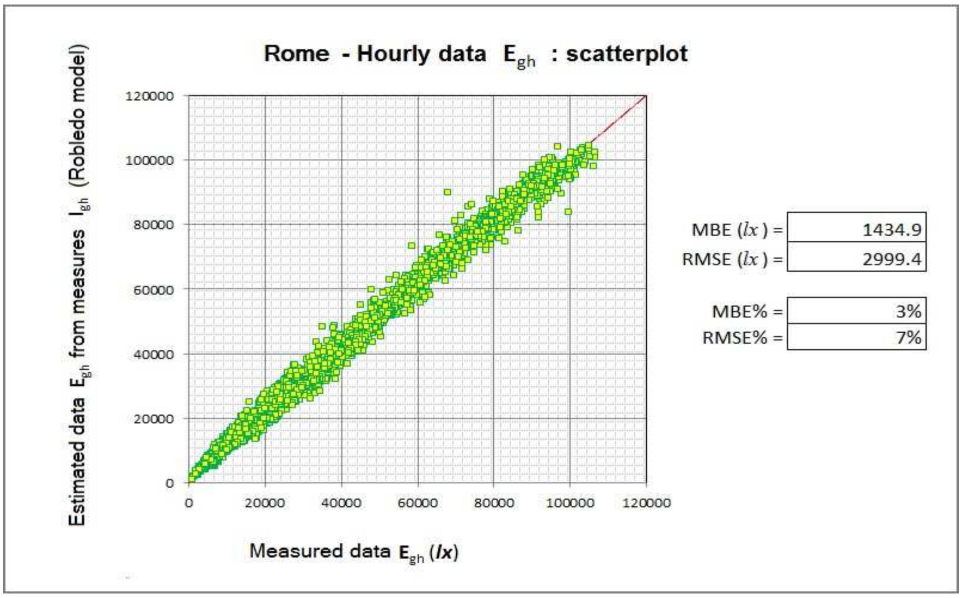

Fig. 6. Comparison: estimated (Robledo model) and measured data for Egh , Rome

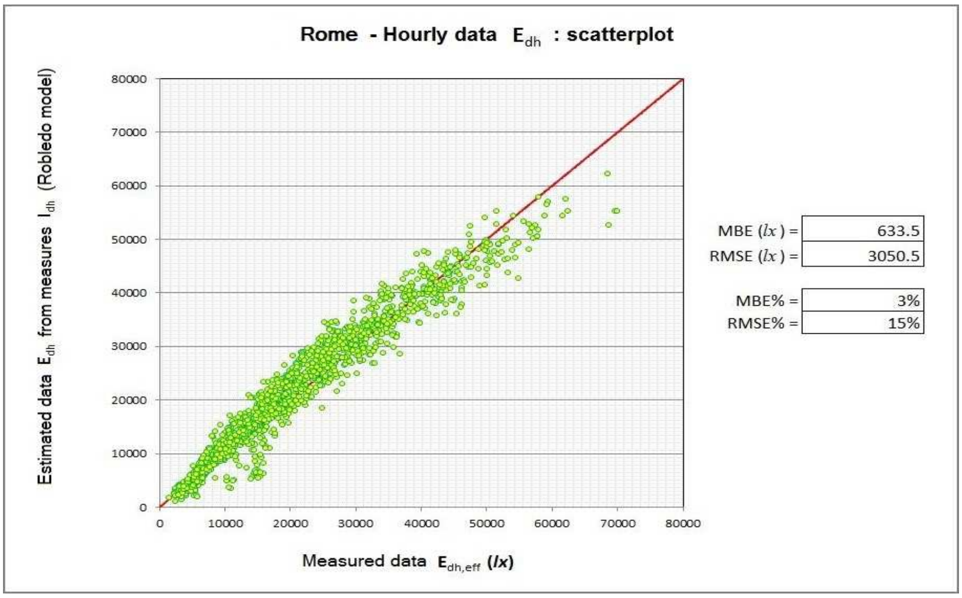

Fig. 7. Comparison: estimated (Robledo model) and measured data for Edh , Rome

The first data processed, for Rome (figs. 6-7), showed low differences between estimated values (R&S model) for Global (Egh) and Diffuse (Edh) illuminance and measured data. The findings have been confirmed by values of statistical indicators, MBE and RMSE, evaluated for both components. The measurements campaign is still ongoing and the further data, related to the other sites selected (Milan and Lampedusa) will allow to get an overall validation of model for Italian territory.

6. Conclusions

This paper presented preliminary studies for the preparation of a national atlas of illuminance data for building applications. Relevant models of luminous efficacy starting from solar radiation data were screened, in order to find the most suitable solution, in terms of accuracy and availability of the relevant input parameters.

Different illuminance hourly TMYs where hence built and comparisons were carried out in terms of daylight availability and autonomy. Discrepancies of the models in reproducing the diffuse component of the photometric quantities were highlighted. A reference model for the future national database was selected and compared with first land measurements data.

Preliminary results were presented to show how the data could be used for building applications. Further tests are ongoing to check, with ground measurements, the accuracy of the luminous efficacy models and eventually introduce refinements and adjustments. Final steps are: establish outdoor illuminance availability diagrams for main Italian towns for different operating times and plot Italian Daylight maps.

References

[1] Communication from the Commission of 3 March 2010 - Europe 2020. A strategy for smart, sustainable and inclusive growth [COM(2010) 2020 final – Not published in the Official Journal].

[2] Communication from the Commission to the European Parliament, the Council, the Economic and Social Committee and the Committee of the Regions of 8 March 2011 – Energy Efficiency Plan 2011 [COM(2011) 109 final – Not published in the Official Journal].

[3] Piano d’Azione Italiano per l’Efficienza Energetica (2013).

[4] Energy performance of buildings EU Directive (EPBD2) 2010/21/EU.

[5] EC (European Commission), www.ec.europa.eu/comm/energy_transport/atlas/html/buildings.html, 2007.

[6] DOE (U.S. Department of Energy). Building Energy Data Book available from: http://buildingsdatabook.eren.doe.gov/, 2009.

[7] IDEA (Instituto para la Diversificación y Ahorro de la Energia). Plan de Ación de Ahorro y Eficiencia Energética 2011–2020 – Annexo. Action Plan From the Spanish Government, Madrid, Spain, 2011.

[8] P.A. Enkvist, T. Nauclér and J. Rosander. A cost curve for greenhouse gas reduction: a global study of size and cost of measures to reduce greenhouse gas emissions yields important insights for businesses and policy makers, McKinsey Quarterly: the online journal of McKinsey & Co 1, 2007.

[9] EN 15193:2007. Energy performance of Buildings. Energy requirements for lighting. Eason, B. Noble, and I.N. Sneddon, “On certain integrals of Lipschitz-Hankel type involving products of Bessel functions,” Phil. Trans. Roy. Soc. London, vol. A247, pp. 529-551, April 1955.

[10] C.F. Reinhart and O. Walkenhorst. Validation of dynamic RADIANCE-based daylight simulations for a test offi ce with external blinds. Energy and Buildings Vol. 33 (2001), 683–697

[11] C.F. Reinhart and D.A. Weissman. The daylight area – correlating architectural student assessments with current and emerging daylight availability metrics. Building and Environment, Vol. 50 (2012), 155–164.

[12] S. Wittkopf and L.O. Grobe, (2013). Climate-based daylight simulation as a planning aid for the design of solar façades. Proceedings of Energy Forum Building Skins (153-157). Brixen, Italy: Energy Forum.

[13] M. Zinzi and A. Mangione, The Daylighting Contribution in the Electric Lighting Energy Uses: EN Standard and Alternative Method Comparison, Energy Procedia, Volume 78, November 2015, Pages 2663-2668

[14] SolarItaly – Atlante italiano della radiazione solare, http://www.solaritaly.enea.it.

[15] Clisun - Archivio Climatico ENEA-DBT, http://clisun.casaccia.enea.it.

[16] S. Petrarca, E. Cogliani and F. Spinelli (2000), La radiazione solare globale al suolo in Italia. Anni 1998 e 1999 e media 1994-1999, ENEA, Roma.

[17] F. Spinelli, E. Cogliani, A. Maccari and M. Milone (2007), La misura e la stima della radiazione solare:

l'archivio dell'ENEA e il sito Internet dell'Atlante italiano della radiazione solare per la pubblicazione dei dati, Rapporto tecnico ENEA SOL/RS/2007/21, Roma.
http://www.solaritaly.enea.it/Documentazione/ArchivioRadiazioneSolaritaly.pdf

[18] European Organisation for the Exploitation of Meteorological Satellites (EUMETSAT), http://www.eumetsat.int.

[19] D. Cano, J.M. Monget, M. Albuisson, H. Guillard, N. Regas and L. Wald (1986), "A method for the determination of the global solar radiation from meteorological satellite data", Solar Energy, 37, 31–39, Elsevier.

[20] J. Boland and B. Ridley (2008), Models of Diffuse Solar Fraction, in Modeling Solar Radiation at the Earth's Surface, Springer-Verlag Berlin Heidelberg, cap. 8, p. 193-219.

[21] D.G. Erbs, S.A. Klein and J.A. Duffie (1982), Estimation of the Diffuse Radiation Fraction for Hourly, Daily, and Monthly-Average Global Radiation, Solar Energy, vol. 28, 1982, p.13

[22] M. Cucumo, A. De Rosa, V. Ferrero, D. Kaliakatsos and V. Marinelli (2004), Correlazioni sperimentali dell'efficacia luminosa della radiazione globale, diretta e diffusa, 59° Congresso ATI, Genova, Settembre 2004.

[23] T. Muneer and D. Kinghorn (1998), Luminous efficacy models: evaluation against UK data, Journal of the IES 1998; 27(1):163-70.

[24] R.R. Perez, P. Ineichen, R. Seals, J. Michalsky and R. Stewart (1990), Modeling daylight availability and irradiance components from direct and global irradiance, Solar Energy 44, 5 (1990), pp. 271-289.

[25] L. Robledo and A. Soler (2000), Luminous efficacy of global solar radiation for clear skies, Energy Conversion & Management, 41 (2000):1769-1779.

[26] L. Robledo and A. Soler (2001), Luminous efficacy of direct solar radiation for all sky types, Energy, 26 (2001):669-677.

[27] L. Robledo and A. Soler (2001), On the luminous efficacy of diffuse solar radiation, Energy Conversion & Management, 42 (2001):1181-11