Development of Daylight Availability Maps in Italy: methodology and validation.

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Abstract

This paper describes a study aimed at providing outdoor illuminance data in Italy, to be used to evaluate daylight potential contribution in the energy performance of buildings. Starting from solar radiation data, a luminous efficacy model was implemented to derive outdoor illuminance for Italian territory. The results obtained were compared with ground measurements, carried out in three different Italian sites (Milan, Rome and Lampedusa island), and the accuracy of model, has been improved introducing specific metrics for Italian context. Typical Meteorological Years (TMYs) of global and diffused components of daylight illuminance, were built for 243 locations, considering different time profiles. Since the definition of the spatial and temporal trend of environmental variables or metrics requires the application of appropriate interpolation procedure, geostatistic methods (kriging), was used to develop Italian daylight maps. The daylight availability maps will be included in the Italian database of solar radiation (www.solaritaly.enea.it) providing an useful tool for lighting energy performances in buildings applications.

key-words: Daylight illuminance, Daylight availability maps, kriging

1. Introduction

The natural light plays a crucial role on the energy and environmental performances, as well as on the users' comfort and architectural integration in building applications. As for other energy uses, also lighting calls for a closer relationship between the building and its climatic context, with growing interest towards climate based assessment method for the daylighting estimation.

Relevant studies were carried out during the past years to support the design of energy efficient and sustainable buildings, where the daylight play a central role in defining the design and assessment priorities [1, 2]. On the other side, the energy uses for lighting play a significant role in the overall energy performance of buildings, as addressed by the relevant European Directive [3] and documented by several papers [4, 5].

Whether it is design or assessment, a critical aspect to evaluate the energy saving potential of lighting is the assessment of the daylight contribution. The energy need for electric lighting in European buildings, is currently determined according to the procedure defined in EN15193:2007 [6], implemented as a national technical standard also in Italy. Several studies, carried out in previous years, highlighted the limits of related calculation method, in which daylight data of the sites are not taken into account [7].

In the framework of the Italian national research programme “Ricerca di Sistema Elettrico”, an alternative calculation method was proposed [8], in which the diffused horizontal illuminance is used as a climate parameter to estimate the availability of daylight in buildings and, consequently, to evaluate the energy needs for artificial lighting [9]. It is widely known that climate–based daylight modeling (CBDM) can provide better support than currently-used simplified methods, in daylight prediction under realistic conditions. [10] On the other hand, the implementation of CBDM method require a large dataset of daylight measures to derive a cumulative curves of daylight availability for different zone.

This paper deals with the application of above calculation methodology applied to build Typical Meteorological Years (TMYs) for outdoor illuminance and develop daylight availability maps for the Italian territory.

doi:10.18086/swc.2019.42.10 Available at http://proceedings.ises.org

2. Methodology

The definition of a luminous efficacy model, allows to convert radiometric quantities (Global, Diffuse and Direct Irradiance [kWh/m^2]) into photometric quantities (daylight illuminance [lux]). Starting from satellite data provided by the EUMETSAT, [11]. ENEA developed, during the past years, the national solar radiation atlas in Italy, implementing validated models to predict the global, direct and diffuse irradiation [12,13]. In this work, Italian data base for solar radiation has been used to derive maps for daylight illuminance [14]. 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 location on the earth surface.
As described in previous work [15], the analysis of existing models for luminous efficacy, led to the choice of Robledo & Soler model (R&S) for the first application [16,17,18,19].

Robledo & Soler Luminous efficay model

$$\begin{cases} E_{gh} = \eta_{gh} I_{gh} \qquad E_{dh} = \eta_{dh} I_{dh} \qquad E_{bn} = \eta_{bn} I_{bn} \\ \\ \eta_{dh} = \alpha \Delta^{-\beta} \; lm \cdot W^{-1} \\ \eta_{bn} = \gamma \cos^{\delta} \vartheta_z e^{-\varepsilon(90^\circ - \vartheta_z)} (\mu - \rho\Delta) \; lm \cdot W^{-1} \\ \eta_{gh} = \eta_{bn}(1-k) + \eta_{dh} k \\ \\ k = I_{dh} / I_{gh} \\ \Delta = m I_{dh} / I_{0n} \end{cases} \tag{1}$$

in which:

$I_{gh} \quad I_{dh} \quad I_{bn}$	*global horizontal irradiance*, *diffuse horizontal irradiance* and *direct normal irradiance*. The three quantities are linked by the following equation: $I_{gh} = I_{bn} \cos\vartheta_z + I_{dh}$ (2)
I_{0n}	is the extra atmospheric normal irradiance;
$E_{gh} \quad E_{dh} \quad E_{bn}$	global, diffuse and direct illuminance;
$\eta_{gh} \quad \eta_{dh} \quad \eta_{bn}$	are global, diffuse and direct louminouse efficacy;
k	is the fraction of diffuse Irradiance on the horizontal plane;
ϑ_z	zenith angle;
Δ	is *sky's brightness index*. This index is indicative of the cloudiness level;
m	*relative optical air mass* (relative measure of path length which Solar radiation takes through the atmosphere);
$\alpha, \beta, \gamma, \delta, \varepsilon, \mu$ e ρ	adimensional metrics based on statistical regression on data measured in Madrid in1994 e 1995:

$$\begin{cases} \alpha = 91.07 \quad \beta = 0.254 \\ \gamma = 134.27 \quad \delta = 0.269 \quad \varepsilon = 0.0045 \\ \mu = 1.045 \quad \rho = 0.427 \end{cases} \tag{3}$$

The extensive measurement compaign, carried out for about two years, allowed to better adaptation to the Italian context, on the basis of the available data, introducing specific adjustments:

- different equation used for calculation of Global component of illuminance (E_{gh})
- different metrics used to calculate the diffuse component of the illuminance (E_{dh})
- direct component of illuminance (E_{dn}) expressed by a linear combination of each other components

The following equations, derived from R&S model, describe the "Italian model" implemented:

Italian Luminous efficay model

$$\begin{cases} \eta_{gh} = \lambda \cos^a \vartheta_z \, e^{-b(90°-\vartheta_z)}(1-\phi\Delta) \\ \eta_{dh} = \alpha\Delta^{-\beta} \\ \eta_{bn} = (\eta_{gh} - \eta_{dh}k)/(1-k) \end{cases} \quad (4)$$

where:

η_{gh} η_{dh} η_{bn} (*Global. Diffuse and Direct luminous efficacy*), k , ϑ_z , Δ , and m , have the same meanings described above, whereas instead $\lambda, a, b, \phi, \alpha, \beta$ are metrics based on experimental measures carried out in Italy.

$$\begin{cases} \lambda = 129.46 \; lm \cdot W^{-1} \\ a = 0.122 \\ b = 0.029 \\ \varphi = 0.07595 \\ \alpha = 85 \; lm \cdot W^{-1} \\ \beta = 0.28 \end{cases} \quad (5)$$

The luminous efficacy model introduced allows to directly calculate the global and diffuse components on the basis of correlation parameters derived from measurements carried out in Italy. Furthermore, unlike the previous model used (R&S), the direct component, less relevant for the estimates of the daylight contribution in buildings, was calculated as a linear combination of the other two. This made it possible to improve the accuracy of the maps of the two most used components, for daylight evaluation in the buildings applications.
The results obtained, have been validated with ground measurements (monitoring period 2015-2017), carried out in three different Italian sites, to test the effectiveness of model, taking into account different latitudes of Italian territory: Milan, Rome and Lampedusa.

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

Tab 1: Measurements station sites

Type of sensor	**Working range [klx]**	**Linearity error-to above level**	**Absolute calibration error [%]**
Lux sensor Skye SKL 310	0-500	< 0.2%	<3%

Tab 2: main specifications of sensors

Due to its barycentric position, it was assumed that the parameters measured in Rome to derive the latitude-dependence illuminance were extended to the whole national territory. The Rome results are following described in an extended way.

The scatter plots below show the comparison between estimated and measured data for the city of Rome:

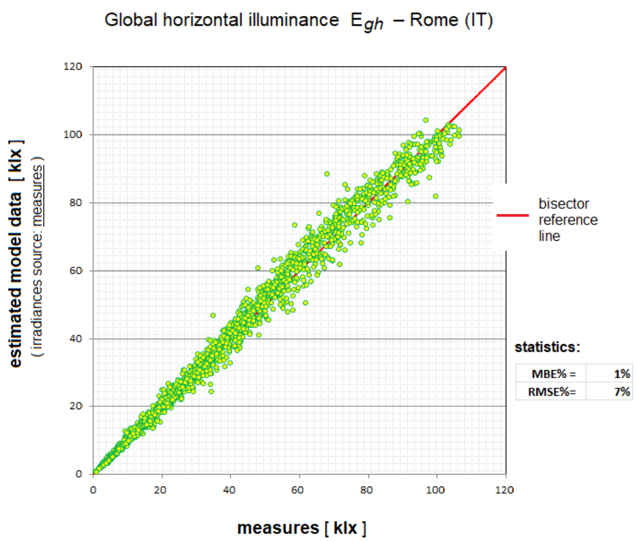

Fig. 1 Comparison: estimated and measured data for Egh, Rome
Application of Italian luminous efficacy model starting from irradiance measurements

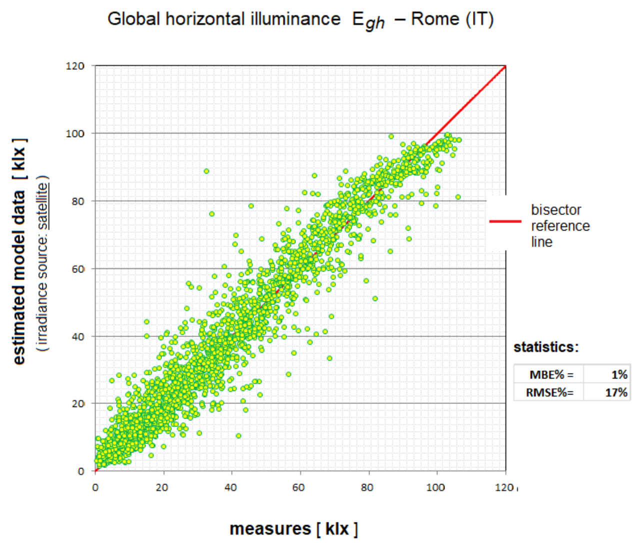

Fig. 2 Comparison: estimated and measured data for Egh, Rome
Application of Italian luminous efficacy model starting from irradiance values derived from satellite data

In both diagrams, the comparison between estimated and measured values of global illuminance is presented. In the first case, the daylight illuminance values were obtained through the Italian model of luminous efficacy, starting from irradiance measured, and tested with illuminance measurements, conducted in the same locality, Rome. The values of statistical indices MBE (1%) and RMSE (7%), show the effectiveness of the model and the accuracy of the parameters introduced. In the second case, similar comparison has been carried out, but the irradiance values used in the model were derived from satellite data. The MBE values, equal to 1%, and the dispersion resulting slightly higher, 17%, confirmed the previous results.

For completeness but in a more condensed way for brevity reasons, also the Milan and Lampedusa results are following presented. As inferred from graphs and indexes, the results prove the validity of the model, even if some minor differences only in RMSE index can be observed (Milan MBE%=-4% RMSE%=30% Lampedusa MBE%=-2%; RMSE%=12%).

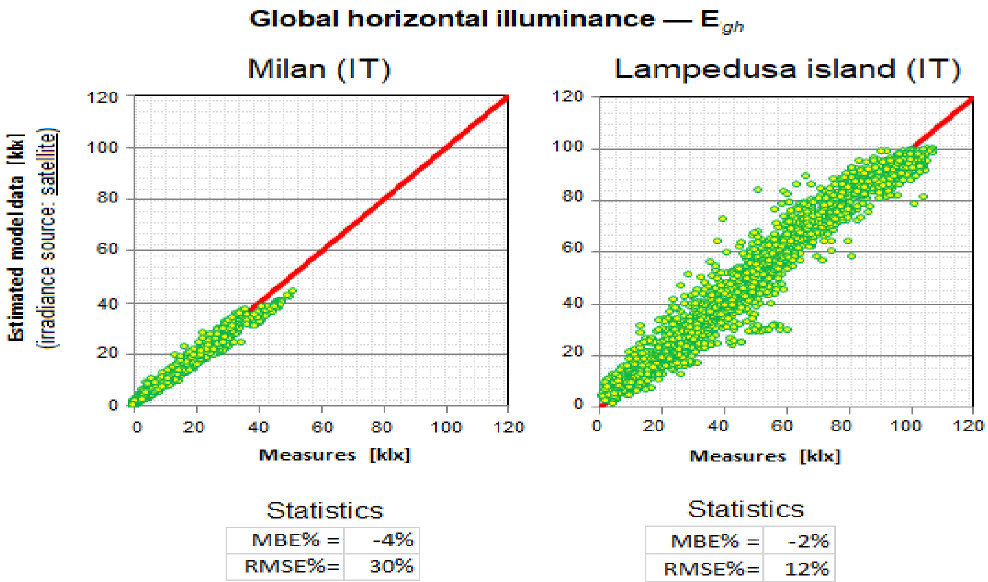

Fig. 3 Comparison: estimated and measured data for Egh, Milan and Lampedusa island
Application of Italian luminous efficacy model starting from irradiance values derived from satellite data

On the base of these findings, it was possible to use the irradiance derived from satellite data, even in locations where direct measurements are not available, and therefore to elaborate maps of natural illuminance for the whole national territory.

3. Results

The luminous efficacy model, as described, has allowed to calculate Typical Meteorological Years (TMYs) for all components of outdoor illuminance (global, diffuse and direct) for 243 Italian sites, considering different time profiles (0:00÷24:00, 8:00÷18:00) selected to evaluate the potential daylight autonomy. Subsequently, from hourly data, monthly and annual daylight availability curves were calculated for the different locations considered.

Fig. 4 presents the cumulative availability of the illuminance components (global, direct, diffuse) for the city of Rome. Figure 5 and 6 present the illuminance availability plots estimated in the reference localities for global and diffuse illuminance, respectively,

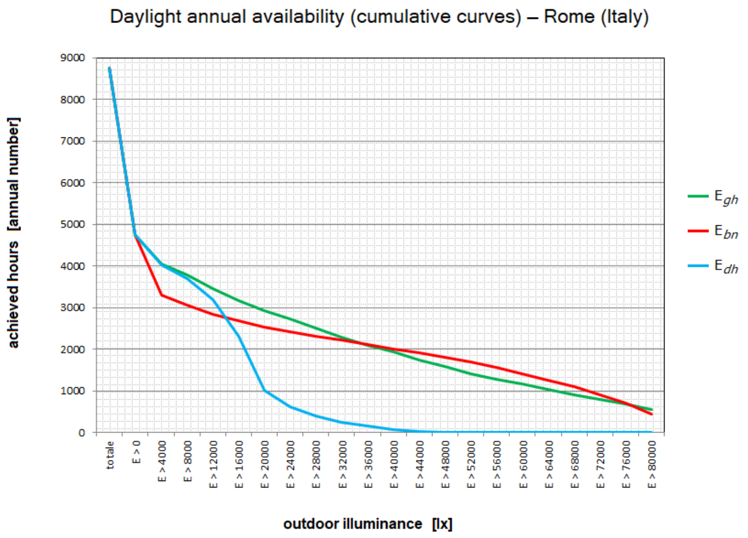

Fig. 4. Illuminance availability Rome, IT

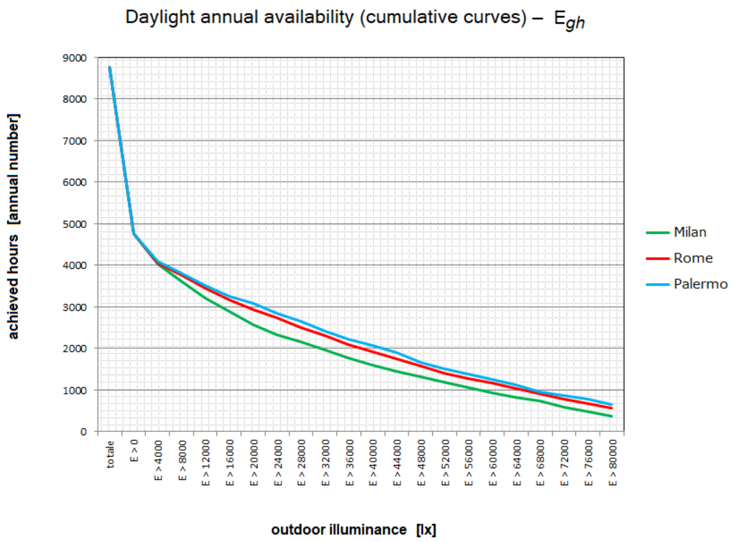

Fig. 5. Global Illuminance availability for different Italian sites

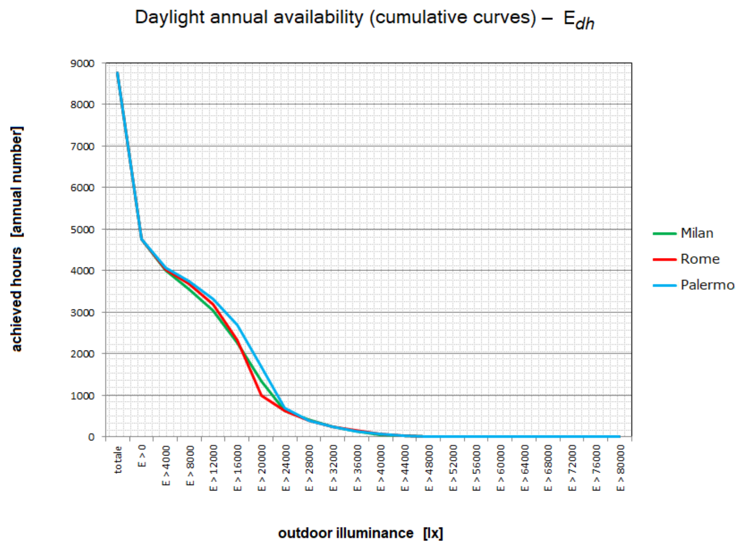

Fig. 6. Diffuse Illuminance availability different Italian sites

The daylight availability expressed by cumulative curves allows to evaluate the percentage of hours in the year in which a specific value of outdoor illuminance is achieved.
The daylighting in the built environment is generally addressed taking into account the diffuse (sky) component, so to work under conservative conditions and to derive the energy need for artificial lighting.
The global component Egh, Fig. 5, is strongly affected by the latitude, so in Palermo, was found the greater outdoor illuminance availability. Different behavior show instead the trends of the diffuse component trends show a different behaviour since it seems to be greater in Milan than in Rome, according to Fig.6. The two curves are very close, but despite a latitude difference of about 4°, intersect at about 18000 and 21000 lux. This aspect, is connected with the climatic and environmental conditions of Milan: the combine effect of duration of the day, and the content of water and aerosol in the air, as a whole, can increase the diffuse component of outdoor illuminance in some periods.
Finally, it is interesting to note the different illuminance values when evaluated for specific time intervals. In the following figure, as an example, the monthly average illuminance calculated for different time profiles are presented, namely: 0÷24 (average daily availability) e 8÷18 (office building operating time).

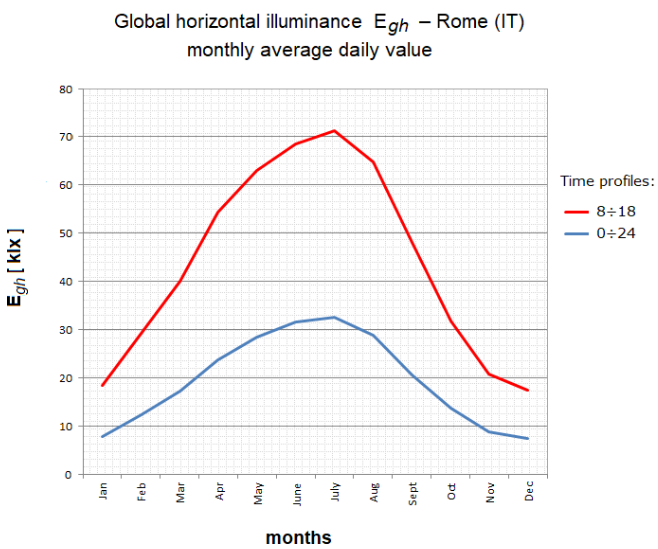

Fig. 7. Global horizontal Illuminance availability for different time profiles, Rome IT

As easily inferred, the values of the average monthly illuminance for the 8÷18 interval are always higher than those relative to the interval 0÷24, although the latter wider. This happens because hourly or daily illuminance, or calculated in any other range, is not instantaneous, but represent average values, defined as:

$$\bar{E}(\Delta t) = \frac{\int_{\Delta t} E(t)dt}{\Delta t} \tag{6}$$

where:

$E(t)$ is the instantaneous value of illuminance,

Δt is the selected time interval (hour, day, month, year, etc.)

$\bar{E}(\Delta t)$ is the average value in the range considered

For this reason, interval 8÷18, not including the evening or early morning hours, in which the irradiance is lower, shows a higher average value.

The final step of the work was the development of daylight maps for the whole Italian territory. Starting from satellite data EUMETSAT [15], applying the previously described calculation model, the solar irradiance data were convert into natural illuminance (lx) for 243 locations. The sites considered, represent an optimal size grid, uniformly distributed throughout the Italian territory, which allows the development of natural illumination maps by interpolation methods, without losing accuracy and reducing processing times. To be noted that this dataset is much more detailed of that of the other climatic parameters (temperature, relative humidity, solar irradiation) included in the national energy performance assessment method, which refer to Provincial capital cities, for a total of 107 sites.

Since the definition of the spatial and temporal distribution of environmental variables or climatic data, requires the application of appropriate interpolation procedure, different spatial analysis methods, were analyzed to be used to develop daylight maps:

- Inverse Distance Weighted (IDW)
- Polynomial interpolation (Spline)
- Nearest Neighbor Analysis (NNR)
- Geostatistics (Kriging)

There is no univocal method for interpolating, but the best one depends on distribution of data points, statistic variability of data, geometry and extension of the study area [21]. The comparisons of the different considered methodology, has allowed to select Ordinary Kriging [22] as the most appropriate method for developing of daylight maps in Italy.

Kriging is a geostatistic method for predicting and generating distribution map of a physical quantity, starting from the spatial autocorrelation of a set of data or measurements. In the basic application, called Ordinary kriging, a weighted average of neighboring points is used to estimate the "unknown" value of another data, in a given location. Weights are estimated by optimization procedure, using all the relationships between known and unknown data [23, 24]. The application of ordinary kriging has allowed to reproduce the natural spatial pattern of daylight illuminance which, unlike other climatic parameters, such as temperature, which also strongly depends on local microclimatic conditions, presents a regular trend, linked, as a first approximation, to the gradient of latitude. In addition, by kriging can be estimate the error associated with the interpolated value, which represents a measure of the uncertainty of the prediction, and therefore an index of the interpolation quality.

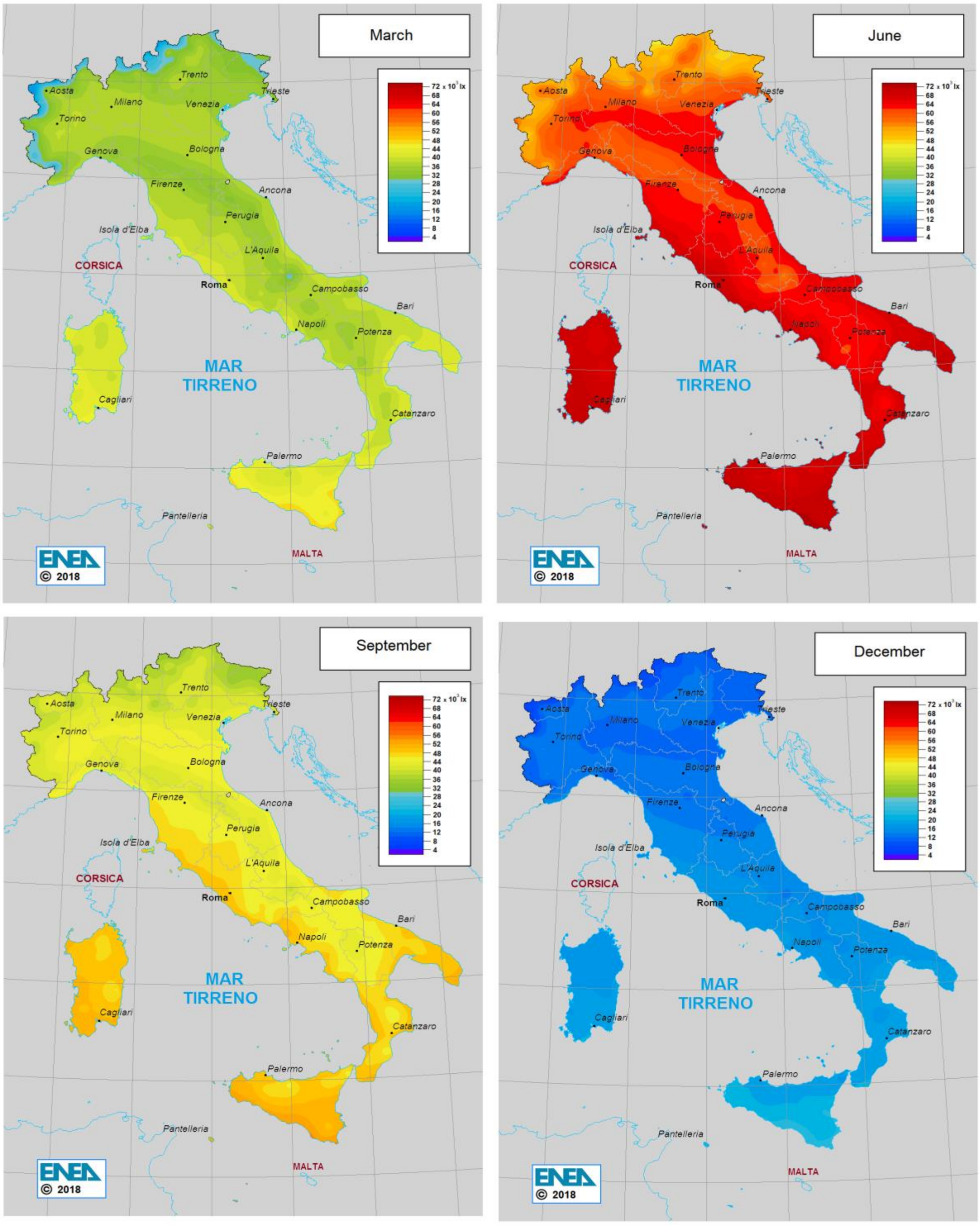

Fig. 8 Daylight illuminance Maps, Italy
Daily average monthly value - Time profile: 8÷18.

4. Conclusions

In this work the methodology and validation procedures carried out to develop Italian daylight maps have been described. Starting from solar radiation data, a luminous efficacy model was defined to derive Outdoor illuminance TMYs for all Italian sites.

Outdoor illuminance series were built in terms of daylight availability for different cities and different operating time in order to show how the data can be used for building applications.

Furthermore, by applying geostatistical interpolation methods, daylight maps have been developed on a monthly and annual scale for the entire Italian territory.

This extensive atlas, inclusive of illuminance and the daylight availability maps, represents a fundamental dataset for the implementation and uptake of Climate Based (CBDM) simulation tools, to be used in daylight prediction in buildings and urban environment applications [25].

The use of daylight site data in climate based methods can play a relevant role in improving the currently used evaluation methods for the lighting energy performance in buildings and urban districts [26]. The cumulative availability of diffuse illuminance, based on climate data, can allows to refine the most common approaches of studying of natural light in buildings, supporting the develop of new metrics and indices to evaluate daylight contribution in indoor space and consequently, improve the definition of energy efficiency actions at design stage [27].

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