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Diffuse solar irradiance estimation on building's façades: Review, classification and benchmarking of 30 models under all sky conditions

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ABSTRACT

Solar energy potential analysis on oriented and tilted surfaces, such as building façades, is of capital importance to estimate the energy production potential in integrated systems, such as BIPVs. The spatial distribution of solar diffuse energy outstands as one of the most critical factors in order to improve performance simulations. Nevertheless, most wide spread models have been only evaluated on equator facing tilted surfaces and with daily mean or hourly mean time ranges. Thus, in this paper, 30 transposition solar diffuse irradiance models, from the semiphysical classical ones to the newest non-parametric models, are reviewed, classified according to their characteristics and evaluated against empirical 10-min averaged diffuse irradiance values gathered from high precision pyranometers placed on vertical positions facing the four cardinal directions. Models' performance is evaluated by several statistical estimators and a benchmark has been carried out by a non-parametrical aggregating procedure. Results show that the most accurate models appear to be the non-parametric ones. From these, The Multi-Layer Perceptron obtains the best results. From the parametric models, the one whose estimations are closest to the measures is the Perez et al. with local optimized coefficients. Perez et al. model with the original coefficients, Skartveit and Olseth and Igawa et al. models also show a good performance.

1. Introduction

It is clear that gaining an in-depth knowledge of the available solar resource is of the utmost importance. It can be used in very different fields, such as meteorological forecasting, biology, agriculture, energy, architecture, and so on. Moreover, it should not be forgotten that knowledge of the potential of solar radiation is necessary for diversifying energy and dimensioning heating and air-conditioning systems, as well as for the intelligent use of renewable energies on most scenarios. The design, dimensioning and calculation of solar-energy-based systems requires precise knowledge of the amount of global irradiance and specially the direct, diffuse and reflected components that fall on surfaces that are horizontal or inclined in any direction. This late case is really worth of interest on the analysis of building's efficiency or solar energy generators performance. The fruit of studies in this field allows the development and implementation of many different systems; for example photovoltaic technology [1–4], the calculation of thermal loads and cooling in buildings [5], the design of efficient solar collectors [6], and an infinite number of other technological applications that have the objective of increasing human well-being and comfort [7,8].

Since the Maastricht Treaty in 1992 [9], the European Union's energy and environmental target has been to promote sustainable and environmentally friendly growth in its member countries. Having set the goal of a 12.5% contribution from renewable energies with respect to total consumption for the year 2010, at the 2004 Berlin Conference [10] the recommendation was made that the percentage of renewable energies for the year 2020 should reach 20% of the total consumption of energy [11]. This was established through the Horizon 2020 plan [12]. Prescriptions were also made in the Kyoto Protocol on climate change [13], which many European countries, including Spain, signed up to. As it is well known, the protocol created an obligation to lower emissions of greenhouse gases such as CO_2, which are produced mainly by the majority of transportation forms and by current systems for generating thermal and electrical energy. Within this framework, one of the paths to the achievement of the stated objectives is the development of new energy strategies within urban environments.

A significant level of energy is consumed in urban environments. Policies focused on distributed generation, net energy balance or the construction of "*Nearly Zero Energy Buildings*" (nZEB) have been supported by both photovoltaic and thermal solar technology through

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Nomenclature

A_i	Anisotropic index, [–]
b	Radiance distribution index, [–]
B	Beam direct irradiance, [W m^{-2}]
B_{ext}	Extraterrestial irradiance, [W m^{-2}]
B_{sc}	Solar constant, [W m^{-2}]
d	Willmott's index of agreement, [–]
D	Diffuse irradiance, [W m^{-2}]
f_b	Shadowing coefficient, [–]
f_c	Blocked circumsolar, [–]
G	Global irradiance, [W m^{-2}]
G_{st}	Standard global irradiance, [W m^{-2}]
h_s	Solar elevation, [rad]
i_{gr}	Rel. ground radiance function, [–]
i_r	Rel. sky radiance function, [–]
I	Sky radiance, [W m^{-2} sr^{-1}]
I_g	Albedo's radiance, [W m^{-2} sr^{-1}]
I_{gz}	Nadith radiance, [W m^{-2} sr^{-1}]
I_z	Zenith radiance, [W m^{-2} sr^{-1}]
k_d	Diffuse fraction, [–]
m	Relative optical air mass, [–]
MBD	Mean Bias Difference, [W m^{-2}]
N	Day of the year, [day]
R	Reflected irradiance, [W m^{-2}]
R^2	Coefficient of determination, [–]
R_b	Tilted beam irradiance fraction, [–]
R_d	Tilted diffuse irradiance fraction, [–]
R_r	Tilted reflected irradiance fraction, [–]
RMSD	Root Mean Squared Difference, [W m^{-2}]
s_c	Circumsolar fraction, [–]
Si	Igawa's sky index, [–]
T_M	Muneer's radiance distribution, [–]

Greek symbols

α	Significance level, [–]
γ	Azimuth angle, [rad]
γ_p	Sensor's azimuth angle, [rad]
γ_s	Sun's azimuth angle, [rad]
Δ	Perez et al.'s brightness index, [–]
δ_s	Sun's declination angle, [rad]
ε	Perez et al.'s clearness index, [–]
θ_z	Zenith angle, [rad]
θ_{zp}	Sensor's zenith angle, [rad]
θ_{zs}	Sun's zenith angle, [rad]
$\mu_{1-\alpha}$	Statistical estimator, [W m^{-2}]
ξ_{gp}	Reflectance angle, [rad]
ξ_{op}	Obstacle-pyranometer angle, [rad]
ξ_p	Sensor-sky point angle, [rad]
ξ_s	Sun-sky point angle, [rad]
ξ_{sp}	Sun-pyranometer angle, [rad]
ρ	Ground's reflectance, [–]
τ	Atmosphere's transmittance, [–]
ϕ_g	Geographical latitude, [deg. N]

their modularity and easy adaptability to any structure. The nZEB concept has been considerably strengthened by European energy policies such as EU Directive 2002/91/EC [14], consolidated in Directive 2010/31/EU [15], which demands that, since 2019, all newly constructed buildings that are property of public entities must be nZEBs, and that by the end of 2020 all newly constructed buildings must be of this type. This new construction trend allows buildings to be practically independent from the electricity network and other energy infrastructure, thanks mainly to the integration of sources of renewable energy in the architectural design (particularly in "*Building Integrated Photovoltaic Systems*" or BIPVs), maximization of ventilation and natural light, a lowering and optimization of consumption, and so on [16,17].

The integration of photovoltaic generators in buildings envelopes, giving rise to BIPV systems, offers immense potential. In Germany, for example, the integration of photovoltaic systems in buildings may allow up to 50% of demand for electricity to be covered [18]. Other studies indicate that there could be electrical energy savings of between 30% and 50% [19]. In any case, there would be a significant advance towards energy sustainability and self-sufficiency and, therefore, this development seems like it will be unstoppable in the coming years. Furthermore, the harnessing of solar energy via building façades can be

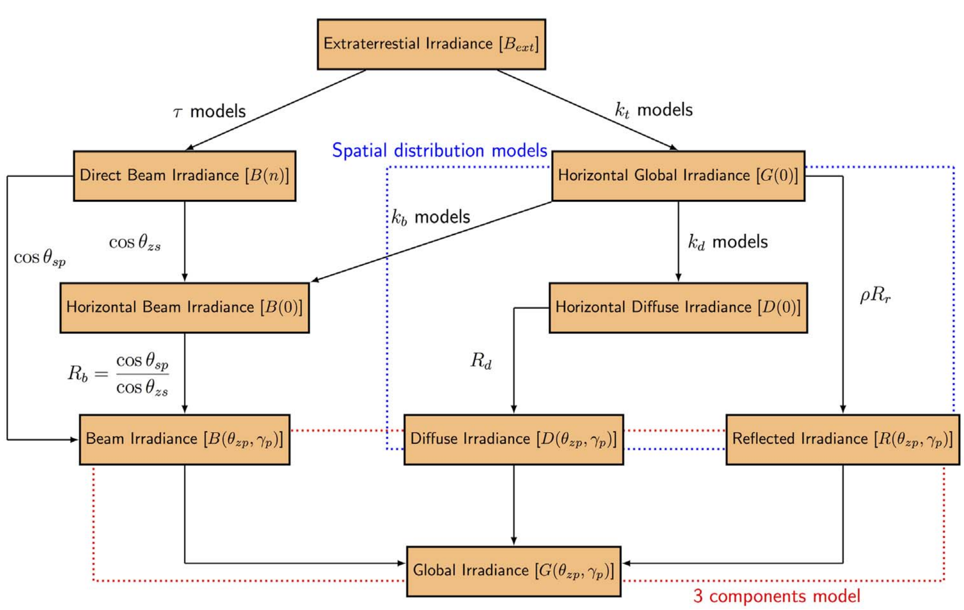

Fig. 1. Solar irradiance modelling flow chart.