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Beam, diffuse and global solar irradiance estimation with satellite imagery

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ABSTRACT

The increase in applications related to solar energy is making it necessary to study those factors related to improving system efficiency and final production. Electricity generation in solar power systems, such as concentrated solar power and photovoltaic plants is governed by meteorological conditions. The presence of attenuating atmospheric factors determines the sun's intermittent character, causing electricity generation instability. Consequently, these fluctuations cause problems when integration the generated electricity into the public electricity grid, resulting in variability and unpredictability in the electricity market.

Therefore, choosing a climatologically optimal place to install solar plants is fundamental for optimizing the final electricity generation. Besides this, constantly-updated solar information can contribute to take transcendental decisions and, consequently, in the performance of solar applications. Accordingly, a real-time solar radiation estimation is presented using satellite images, where beam, diffuse and global components have been evaluated in real time for all sky conditions.

1. Introduction

Reducing the negative environmental and economic factors inherent in traditional electricity generation systems [1] is fundamental if the world is to be free of pollutant gas emissions [2]. In particular, greenhouse gases emissions are producing self-defeating effects in the world, contributing with the climate change, being necessary to choose the best option of renewable energies [3].

Renewable energies systems are presented in form of free pollutant electricity generation systems. In this case, solar energy is tagging as the highest clean and operative renewable energy [4], being one of the most important electricity production sources for the next years [5], in which different reports indicate that 11% of electricity demand for future scenarios will be covered using this kind of renewable energy by 2050 [6]. The process to convert the solar energy into electricity, is mainly carried out using two different alternatives: with CSP or PV plants. CSP plants has been designed to exploit the sun radiation that, for the concentrator character of these plants, only the direct normal irradiance can be used to concentrate the sunlight. This radiation component is concentrated through reflectors onto a receiver (for central tower plants) or cylindrical tubes (for parabolic trough plants). In PV plants, not only direct irradiance is exploited: situations with cloud presence or with atmospheric dispersion, could be suitable to produce electricity. For that, solar radiation is transformed directly into electricity through the photoelectric effect using photovoltaic panels.

Consequently, the influence of the site, in accordance to particular atmospheric conditions, is decisive on the performance of CSP and PV systems. The amount of energy hitting the ground is conditioned by a variety of factors such as the time of year, the sun's position and elevation, and the overall climatological conditions. Climatological changes above solar systems cause alterations in electricity production because the sun is only present intermittently. Consequently, this irregular electricity integrations causes instability in the general electricity grid. As a further consequence, these fluctuations provoke rapid economic changes in the electricity market, making it very difficult to predict the electricity price without taking into account the atmospheric conditions at the time. Subsequently, choosing the best solar plant location is a very important task. For that, the solar irradiance must be studied over a period, mapping the representative solar radiation in order to study and model the solar systems. Besides this, in electricity

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Nomenclature

α	solar altitude (radians)
$\delta_R(m)$	Rayleigh optical thickness
γ	satellite zenithal angle (radians)
ω	input angle (α or γ) (radians)
π	pi constant
ρ	apparent albedo (dimensionless)
ρ_{atm}	intrinsic atmospheric reflectance (%)
ρ_c	cloud albedo (dimensionless)
ρ_{eff}	effective cloud albedo (dimensionless)
ρ_g	ground albedo (dimensionless)
$\sigma_{R_{est,mea}}$	covariance of the two input data sets (the estimated and measured irradiances) [dimensionless]
$\sigma_{R_{est}}$	standard R_{est} deviation (dimensionless)
$\sigma_{R_{mea}}$	standard R_{mea} deviation (dimensionless)
ε	correction used for the variation of the sun-earth distance from its mean value
A_0, A_1, A_2	calibration coefficients for calculating the diffuse angular function (dimensionless)
ANN	Artificial Neural Networks
B_{ESRA}	beam irradiance estimation using the ESRA model (W m^{-2})
CIESOL	Solar Energy Research Center
cos	cosine function
CSP	Concentrated Solar Power
D_{ESRA}	diffuse irradiance estimation using the ESRA model (W m^{-2})
ESRA	European Solar Radiation Atlas
F_d	diffuse angular function
G_{ESRA}	global irradiance estimation using the ESRA model (W m^{-2})
I_0	solar constant equal to 1361 W m^{-2}
I_{met}	maximum irradiance for Meteosat-7 equal to 693.17 W m^{-2}
K_{cs}	clear sky index (dimensionless)
L_{atm}	path radiance (W m^{-2} sr^{-1})
L_{broad}	radiance corrected (W m^{-2} sr^{-1})
$L_{VIS0.6}$	radiance from VIS 0.6 channel (W m^{-2} sr^{-1})
$L_{VIS0.8}$	radiance from VIS 0.8 channel (W m^{-2} sr^{-1})
m	relative optical air mass
MBE	Mean Bias Error (W m^{-2})
MSG	Meteosat Second Generation
N	total number of estimations
n	cloud index (dimensionless)
nMBE	Normalized Mean Bias Error (%)
nRMSE	Normalized Root-Mean-Square Error (%)
PV	photovoltaic
R	correlation coefficient (dimensionless)
R_{est}	irradiance estimation (W m^{-2})
R_{max}	maximum of irradiance measured (W m^{-2})
R_{mea}	irradiance measured (W m^{-2})
R_{min}	minimum of irradiance measured (W m^{-2})
R_{sat}	satellite reflectance (%)
Rad_{ESRA}	irradiance estimation using the ESRA model (W m^{-2})
RMSE	Root-Mean-Square Error (W m^{-2})
s	daily bright sunshine hours
sin	sine function
T_{gr}	global atmospheric transmittance for the upward radiation (%)
T_L	Linke turbidity factor for an air mass equal to 2
T_{rb}	beam transmittance (of the beam radiation) under cloudless skies (dimensionless)
$T_{rd}(T_L)$	transmittance at zenith for diffuse radiation (dimensionless)
T_{sat}	global atmospheric transmittance for the incident radiation (%)
Tr_{beam}	path radiance (W m^{-2} sr^{-1})
UTC	Universal Time Coordinated
VIS 0.6	visible Meteosat channel at 0.6 μm
VIS 0.8	visible Meteosat channel at 0.8 μm

production mode, knowing how much radiation is hitting the ground is powerful information for solar system operators and analysts, allowing an estimation of electricity being generated; and hopefully leading to controlled electricity integration into the public electricity grid. For this reason, estimating any attenuating atmospheric factors is a vital tool for improving the integration of the generated electricity into grid-integration systems, in accordance with meteorological conditions [7].

During the last decades, satellite images are being used to study the atmosphere, amongst others. Clouds, as the highest solar attenuation factor, have been studied for several authors. In Ref. [8], the authors used satellite image to classify the cloud into low, medium and high, depending of height of cloud top. Using another technology, as the case of total sky cameras, clouds have also been studied [9], where clouds were detected using the digital image levels. In this work, the authors solved the problem of saturation of pixels in the sun area, detecting the clouds that appeared in this area [10]. Subsequently, the motion of clouds was analyzed using the cross correlation method [11], comparing the results obtained for cloudiness forecasting with satellite and sky camera in [12]. Nevertheless, the solar radiation study is the fundamental study to define the proper places where the solar plants can be installed. Solar radiation has been analyzed for long periods [13] and estimated over different places using artificial neural network [14]. Furthermore, some authors have studied the solar resource employing, as the case studied in [15], where the authors estimated the solar potential over Turkey using ANN, meteorological and geographical data. Besides this, solar radiation was studied and estimated using different meteorological input data, as the case of study of Algeria [16], where the authors estimated daily global radiation using measured air temperature from a semi-arid location of this country. With regard to solar estimation, one of the most consolidated models for estimating solar radiation under clear skies, developed within the ESRA framework [17], has been used in the Heliosat method [18]. The Heliosat model has been employed to estimate solar radiation alongside different techniques providing accurate results [19,20]. In [19], the authors combined the Heliosat-2 model with digital terrain models, to estimate global daily radiation and the clear sky index (K_{cs}) in a mountainous site, having into account the sun obstruction caused by the presence of mountains. The RMSE values oscillated between 9% and 15% approximately, when the estimated radiation was compared to data from four stations. In [20], global radiation was also estimated using an adaptation of Heliosat-1 model. The model was combined with ground-based linear Ångström–Prescott type relations: the first approach was based on the use of a correlation between daily bright sunshine hours (s) and cloud index (n), whilst in the second approach, a new correlation was proposed between daily solar irradiation and daily data of s and n which is based on a physical parameterization. The authors estimated daily global radiation in 13 different locations and presented the statistical errors in yearly values.

In this work, the three solar radiation components (beam, diffuse and global) have been estimated in real time, for 15 min