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Solar radiation mapping using sunshine duration-based models and interpolation techniques: Application to Tunisia

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ABSTRACT

In this study, several Angström-type regression models, namely the linear, quadratic, cubic, logarithmic and exponential models, are compared to estimate the global solar radiation on horizontal surfaces over a territory. The country of Tunisia is used as a case study for the methodology. The models studied were calibrated using four meteorological stations that are providing global solar radiation and sunshine duration data. The statistical analysis showed that the models assessed are well suited to accurately estimate the solar potential. Overall, the cubic model showed the best regression fit and performed slightly better than the others. However, since the difference between the models studied is insignificant, the linear model has been preferred for the mapping of the solar potential of the study area, mostly because of its simplicity. Two approaches were assessed for the use of the Angström–Prescott parameters: the classical approach which consists of using generic parameters for the whole study area, and a spline interpolation of these parameters. Both methods gave very similar results with a slight improvement for the classical approach which has been employed to map the spatial and temporal distribution of the solar potential of the study area using spline interpolations at a 500 m × 500 m resolution. In application to the territory of the case study, the monthly mean daily global solar radiation in Tunisia varies between 6.9 MJ/m^2/day in the north of the country during January and 28 MJ/m^2/day in June, in the surroundings of the Gulf of Gabes. Annually, the monthly mean daily solar radiation ranges from 15.7 to 19.4 MJ/m^2/day, increasing from north to south.

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1. Introduction

Assessment and mapping of the solar energy potential and its distribution over territories are of capital importance to the development of this energy sector. Solar energy maps can be useful to locate the most suitable locations to install solar systems (concentrated solar power systems and photovoltaic systems), and reduce the costs of feasibility studies for such projects [1].

The best way to map and quantify the global solar radiation over an area would be to gather in situ data over a period of at least one year at multiple stations dispersed over the study area. This could be a costly and a time-consuming operation [2]; which explains the lack of global solar radiation data in most countries, especially in countries in the South.

To overcome this lack of information on the solar energy potential, several solar energy models using different approaches such as regression models, satellite images, artificial neural networks (ANN), fuzzy genetics and support vector machines have been proposed in the literature to estimate the solar radiation [3]. However, the most widely used models to estimate the global solar radiation are empirical models which typically aims to relate the atmospheric transmittance to the extraterrestrial radiation. Angström [4] was the first to propose an empirical model to estimate the global solar radiation based on the sunshine duration. Later, Prescott [5] then Akinoglu [6] developed the Angström model and proposed new empirical models to estimate the solar radiation using the sunshine duration. Bristow and Campbell [7] proposed a model based on temperature. Liu and Scott [8] used the precipitation to develop a model to estimate the solar radiation in Australia. Black [9] based his new model on cloudiness while Elagib el al. [10] proposed a new empirical model to estimate the global solar radiation using the relative humidity. The use of such models to assess and map the solar potential is a relevant and economical alternative to the direct measurements and is a widespread practice across the world.

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Nomenclature

a–d	climatological Angstrom-Prescott regression coefficients
E_0	eccentricity correction factor
G_{sc}	solar constant (G_{sc} = 1367 W/m^2)
H	monthly mean daily global solar radiation on horizontal surface (MJ/m^2)
H_c	monthly mean daily global solar radiation on horizontal surface under clear sky conditions (MJ/m^2)
H_0	monthly mean daily extraterrestrial solar radiation on horizontal surface (MJ/m^2)
J_d	Julian day
n	monthly mean daily sunshine duration (h)
N	monthly average maximum daily sunshine duration (h)
R^2	coefficient of determination
t_{sta}	t-statistic test

Greek letters

δ	solar declination angle (°)
φ	latitude of the site (°)
ω_s	sunrise hour angle (°)

Acronyms

AIC	Akaike information criterion
MABE	mean absolute bias error
MAPE	mean absolute percentage error
MBE	mean bias error
MPE	mean percentage error (%)
RMSE	root mean square error
SBC	Schwartz Bayesian criterion

In their work, Besharat et al. [11] reviewed the extensive empirical global solar radiation models and classified them into four main categories: sunshine-based, temperature-based, cloud-based and other meteorological parameters-based models. The authors applied then four models, one of each category, to Yazd city in Iran and compared their accuracies. According to their results, the sunshine-based model performed better than the other models and returned the most accurate results. Mecibah et al. [12] evaluated and compared a total of eleven empirical models based on sunshine duration and air temperature for six Algerian cities. Their results confirm those of the aforementioned study, since they found that the sunshine-based models, particularly the quadratic and the cubic models, are more accurate than the air temperature-based models. Liu et al. [13] applied five sunshine-based models and three air temperature-based models at Gaize in the Tibetan Plateau using five years of measurements. The statistical comparison of the models considered showed that, in general, the sunshine-based models are more accurate than the air temperature-based models. Li et al. [14] evaluated a total of six sunshine-based and temperature-based models in Mainland China. Their results showed that the sunshine-based models are more accurate than the temperature-based models. Teke and Yildirim [15] applied linear, quadratic and cubic Angström type models to Eastern Mediterranean and proposed monthly regression equations to estimate the global solar radiation. El Ouderni et al. [16] focused on the gulf of Tunis in Tunisia and proposed a model to estimate the hourly solar radiation. Al-Mostafa et al. [17] tested the performance of 52 existing sunshine-based models in Jouf, Saudi-Arabia and found that only 20 of them are suitable for use in this region. Zhao et al. [18] proposed a new approach to estimate the solar radiation using sunshine duration and air pollution index.

Furthermore, several researchers applied these empirical models for estimating the solar radiation in order to produce solar energy atlases and maps. Pan et al. [19] calibrated a regression model to estimate the global solar radiation from air temperature and applied it to map the spatial distribution of solar radiation over the Tibetan Plateau. Cyr et al. [1] proposed a model for the province of New Brunswick in Canada and mapped the solar potential of this Canadian province. Al-Lawati and Dorvlo [20] developed a model to estimate the global solar radiation over Oman and produced some solar radiation contour maps for this country. Griffin and Chavula [21] proposed a linear regression model to estimate the global solar radiation over Malawi and used this model to map the spatial distribution of the monthly solar radiation in this African country. Duzen and Aydin [22] applied and evaluated five regression models to estimate the global solar radiation over the Lake Van region in Eastern Anatolia and then used the most suitable model to map the solar radiation in this territory. Chen and Li [23] proposed a linear regression model, using only three calibration meteorological stations, to estimate and map the global solar radiation over the Chinese Liaoning province.

The first model to estimate the global solar radiation from other meteorological parameters was proposed by Angström [4]. Using the sunshine duration as the model's input, Angström established a linear regression relationship between the ratio of the daily global solar radiation (H) to the clear sky daily global solar radiation (H_c) and the fractional bright sunshine ratio. The latter is the ratio of the measured daily sunshine duration (n) to the maximum possible sunshine duration (N), which represents the length of the daytime.

The difficulty of using the Angström model consists in measuring the clear sky daily global solar radiation (H_c). Prescott [5] modified the model by replacing the latter parameter (H_c) by the extraterrestrial solar radiation (H_0) which is easier to compute. Later, based on the Angström–Prescott model, scientists developed higher degree correlations between the global solar radiation and the sunshine duration.

This study has four main objectives: (1) Compare and validate several sunshine-based models, including the Angström–Prescott model, for estimating global solar radiation on horizontal surfaces using a limited number of calibration meteorological stations; (2) define the Angström–Prescott formula that can be used to estimate the global solar radiation at stations measuring sunshine duration; (3) compare different interpolation techniques for the mapping of solar radiation over a territory; and, (4) produce annual and monthly maps of the mean daily global solar radiation for the territory of the case study, i.e. Tunisia, a north African country facing important challenges in its energy sector, according to the National Agency for Energy Conservation [24].

Besides allowing the identification of a suitable model to estimate the global solar radiation over a territory, this work presents and validates a simple, low-cost methodology to assess the global solar radiation over a territory characterized by limited measurement data.

2. Methodology

2.1. Input meteorological and topographical data

The input meteorological data needed to compare the sunshine-based models for estimating the global solar radiation

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