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# Empirical models for estimating solar radiation in Algeria: A review and case study

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**Résumé** – *Les modèles de rayonnement solaire reste pratiquement l'un des seuls moyens pour pallier au problème des données radiométriques à cause de la rareté des stations météorologiques sur le territoire national parce que les instruments de mesure sont chers et de les installer. Le présent travail propose une étude bibliographique sur les travaux de recherche réalisés pour développer des modèles empiriques de rayonnement solaire en Algérie. De plus et afin de contribuer aux efforts nationaux, trois (03) modèles empiriques se basant sur la durée d'ensoleillement pour estimer le rayonnement solaire global ont été développés dans la région d'Illizi. Les données météorologiques journalières de 2007 à 2014 ont été utilisées pour l'étalonnage des modèles et les données de 2015 à 2018 ont été utilisées pour valider ces modèles. Les résultats de validation ont montré que les équations empiriques linéaire, quadratique et cubique donnent des valeurs très précises du rayonnement solaire global moyen mensuel sur une surface horizontale, avec des petites erreurs statistiques entre les valeurs mesurées et estimées.*

**Abstract** -*The information about solar radiation is limited in space and time at different local regions around Algeria due to the cost of instrumental requirements. Therefore, a number of models have been developed in different regions to estimate incident solar radiation. This contribution includes a review of research works carried out in the development of empirical solar radiation models in Algeria. Furthermore, in order to contribute to the national efforts in establishing solar radiation, sunshine duration empirical models for estimating global solar radiation were developed in the Sahara desert area of Illizi region. Daily meteorological data during 2007 - 2014 were used for models calibration and the data from 2015 to 2018 were used to validate the models. The results revealed that linear, quadratic and cubic empirical equations give very high accurate values of monthly mean daily global solar radiation on a horizontal surface, with smaller statistical testes between measured and estimated values.*

**Keywords**: Solar radiation - Empirical model - Sunshine duration - Illizi.

## 1. INTRODUCTION

Nowadays in Algeria, the renewable energy resources especially solar energy offer interesting opportunities for facing the important increase in electricity consumption, this strategic is motivated by the huge solar energy potential in southern regions.

In the first step hybrid concentrated solar power plant was installed in the south of Algeria (Hassi R'Mel) since 2010 with 180 000 $m^2$ area of parabolic reflectors and 25 MW electrical powers [1]. In February 2011, the government launched the renewable energies program to exports from photovoltaic, wind, biomass, cogeneration, geothermal and thermal solar power plants.

The program is revised in May 2015 and the renewable energies especially solar energy (13 575 MW photovoltaic and 2 000 MW thermal power) should achieve more

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than 22 000 MW (37 %) of national electricity production by 2030 [2]. Solar radiation data is generally important for the optimal design of the solar systems, many approaches have been proposed in several studies to estimate solar radiation around the world with a sufficient accuracy.

These methods are classified into five categories: theoretical models [3], empirical models [4], artificial intelligence models [5], statistical models [6] and satellite imagery models [7]. It is shown from the literature that the empirical and theoretical techniques are widely used for solar radiation estimation because of their simplicity. The empirical models are based on the different meteorological parameters such as air temperature, sunshine duration, clearness index and relative humidity and generally the sunshine based models have been reported to give better estimation [8].

When the meteorological and radiometric measurement stations are not available, the alternatives are the theoretical models. The inputs of these models are the astronomical, atmospheric and geographical parameters. According to Hassan *et al.* [3] the theoretical models were at the same accuracy level with the empirical models when sunshine fraction is not an input.

The chief goal of this investigation is to present a review on the different empirical methods reported in the literature to estimate solar radiation in Algeria. In the other hand, sunshine duration based models are developed for the first time in Illizi region for predicting monthly average daily global solar radiation.

## 2. OVERVIEW OF THE EMPIRICAL MODELS USED IN ALGERIA

In the present section, the radiation models are presented and classified based on their years of appearance.

### 2.1 Chegaar *et al.* models

Chegaar *et al.* [9] proposed tree models based on sunshine duration for estimating monthly mean daily global solar radiation on a horizontal surface in Algiers, Oran, Beni Abbès and Tamanrasset.

*For Algiers and Oran

$$\left(H / H_0\right) = 0.309 + 0.368\left(S / S_0\right) \tag{1}$$

*For Beni Abbès

$$\left(H / H_0\right) = 0.367 + 0.367\left(S / S_0\right) \tag{2}$$

*For Tamanrasset

$$\left(H / H_0\right) = 0.233 + 0.591\left(S / S_0\right) \tag{3}$$

$H_0$ is the monthly mean daily extraterrestrial solar irradiance and $H$ is the monthly mean daily global solar irradiance on a horizontal surface (in MJ/m$^2$.day), $S$ is the monthly mean daily sunshine duration (in hours).

### 2.2 Koussa *et al.* model

Based on different empirical models proposed in the literature, Simulink program has been developed by Koussa *et al.* [10] to estimate the monthly mean hourly and daily global and diffuse irradiations in Adrar, Bouzareah and Ghardaia. After testing the retained models are given by the following equations:

-Monthly mean daily global solar radiation

$$\left(H / H_0\right) = 0.18 + 0.62\left(S / S_0\right) \tag{4}$$

$$\left(H/H_0\right) = 0.29\cos\varphi + 0.52\left(S/S_0\right) \quad \varphi \le 60° \tag{5}$$

$$\left(H/H_0\right) = 0.414 - 0.4\left(S/S_0\right) - 0.0055\,H_a \tag{6}$$

$$4.7923 + 0.3647\,T_a + 0.0055\,T_a^2 + 0.0003\,T_a^3$$

Where $H_a$ is the atmospheric water vapour content per unit volume of dry air, $HR$ is the mean relative humidity per day in the month and $T_a$ is the dry air temperature (in degree Celsius).

-Monthly mean daily diffuse solar radiation

$$\left(H_d / H\right) = 1 - 1.13\left(H / H_0\right) \tag{7}$$

*For $0.3 < H/H_0 \le 0.7$

$$\left(H_d / H\right) = 1.39 - 4.027\left(H / H_0\right) + 5.531\left(H / H_0\right)^2 - 3.108\left(H / H_0\right)^3 \tag{8}$$

*For $0.3 < H/H_0 \le 0.8$ and $\omega_s \le 1.4208$

$$\left(H_d / H\right) = 1.391 - 3.56\left(H / H_0\right) + 4.189\left(H / H_0\right)^2 - 2.137\left(H / H_0\right)^3 \tag{9}$$

$$\left(H_d / H\right) = 1.311 - 3.022\left(H / H_0\right) + 3.427\left(H / H_0\right)^2 - 1.821\left(H / H_0\right)^3 \tag{10}$$

Where $H_d$ is the monthly mean daily diffuse solar irradiance on a horizontal surface (in $MJ/m^2$ . day) and $\omega_s$ is a sunset hour angle (in radians).

-Monthly mean hourly global and diffuse solar radiations

$$r_t = \frac{1}{\sqrt{2\pi\sigma}}\exp\left(-\frac{(t_s - 12)^2}{2\sigma^2}\right) \tag{11}$$

$$r_d = \frac{\pi}{24}\left(\frac{\cos(\omega) - \cos\left[(\omega)\right]_s}{\sin\left[(\omega)\right]_s - \frac{\pi\omega_s}{180}\cos(\omega_s)}\right) \tag{12}$$

Where $r_t$ and $r_d$ are the ratio hourly to daily of global and diffuse solar radiation respectively, $t_s$ is the true solar time ( in hours), $\omega$ is the solar hour angle (in radians) and $\sigma$ is defined by

$$\sigma = 0.2\,S_0 + 0.378 \tag{13}$$

### 2.3 Boukelia *et al.* model

In order to correlating monthly mean daily diffuse solar radiation, Boukelia *et al.* [11] expressed the ratio of diffuse to global radiation by a linear, quadratic, cubic, logarithmic and exponential equation of the ratio of sunshine duration and global solar radiation data at six Algerian stations: Algiers, Constantine, Ghardaia, Bechar, Adrar, and Tamanrasset.

This study finds that the quadratic and cubic equation which based on global solar radiation performed the best accuracy. The best model for the six Algerian stations and the general models for other Algerian locations are summarized below:

Algiers

$$\left(H_d / H\right) = -0.156 + 3.083\left(H / H_0\right) - 3.824\left(H / H_0\right)^2 \tag{14}$$

Constantine

$$\left(H_d / H\right) = 1.46 - 5.326\left(H / H_0\right) + 9.726\left(H / H_0\right)^2 - 6.736\left(H / H_0\right)^3 \quad (15)$$

Ghardaia

$$\left(H_d / H\right) = -2.313 + 7.393\left(S / S_0\right) - 5.314\left(S / S_0\right)^2 \quad (16)$$

Bechar

$$\left(H_d / H\right) = -0.1686 - 3.377\left(H / H_0\right) + 1.859\left(H / H_0\right)^2 \quad (17)$$

Adrar

$$\left(H_d / H\right) = 3.494 - 9.025\left(H / H_0\right) + 6.224\left(H / H_0\right)^2 \quad (18)$$

Tamanrasset

$$\left(H_d / H\right) = 0.311 + 0.078\left(S / S_0\right) - 0.314\left(S / S_0\right)^2 \quad (19)$$

Algeria

$$\left(H_d / H\right) = 0.037 - 0.068\left(H / H_0\right) + 0.025\left(H / H_0\right)^2 - 0.002\left(H / H_0\right)^3 \quad (20)$$

$$\left(H_d / H\right) = 0.2763 - 0.0078\left(H / H_0\right) - 0.0002\left(H / H_0\right)^2 \quad (21)$$

## 2.4 Mecibah *et al.* model

Mecibah *et al.* [12]correlating the monthly mean daily global solar radiation on a horizontal surface with monthly mean sunshine records and air temperature data for six Algerian cities: Algiers, Oran, Batna, Ghardaia, Bechar, and Tamanrasset.

After testing, the sunshine based models appear to be more accurate than air temperature based models. The best model in these regions and the general models for other Algerian locations are given in fallowing equations:

Algiers

$$\left(H / H_0\right) = 1.663 - 5.373\left(S / S_0\right) - 7.533\left(S / S_0\right)^2 - 3.081\left(S / S_0\right)^3 \quad (22)$$

Oran

$$\left(H / H_0\right) = 15.57 - 70.09\left(S / S_0\right) + 106.3\left(S / S_0\right)^2 - 53.581\left(S / S_0\right)^3 \quad (23)$$

Ghardaia

$$\left(H / H_0\right) = 8.097 - 28.62\left(S / S_0\right) + 36.47\left(S / S_0\right)^2 - 15.32\left(S / S_0\right)^3 \quad (24)$$

Bechar

$$\left(H / H_0\right) = 11.63 + 26.88\left(S / S_0\right) + 16.47\left(S / S_0\right)^2 \quad (25)$$

Batna

$$\left(H / H_0\right) = 2.003 - 6.883\left(S / S_0\right) + 10.29\left(S / S_0\right)^2 - 4.826\left(S / S_0\right)^3 \quad (26)$$

Tamanrasset

$$\left(H / H_0\right) = -1.806 + 8.705\left(S / S_0\right) - 10.03\left(S / S_0\right)^2 - 3.848\left(S / S_0\right)^3 \quad (27)$$

Algeria

$$\left(H / H_0\right) = 0.57211 - 0.00901\left(S / S_0\right) + 0.00028\left(S / S_0\right)^2 - 0.00002\left(S / S_0\right)^3 \quad (28)$$

$$\left(H / H_0\right) = 0.57089 - 0.21028\left(S / S_0\right) + 0.00005\left(S / S_0\right)^2 \quad (29)$$

## 2.5 Yacef *et al.* model

Six new combined empirical models have been used by Yacef *et al.* [13] to estimate daily global solar radiation from air temperature on a horizontal surface in Ghardaïa.

These models combine six standards empirical models and linear regression (left part) based on the developed model by Daut *et al.* [14].

Model 1: $$0.0148x + 0.4416 = 0.6653 H_0 \left(1 - \exp\left(-0.028 DT^{1.9324}\right)\right) \tag{30}$$

Model 2: $$0.0153x + 0.4347 = 0.6676 H_0 \left(1 - \exp\left(-0.0380 DT^{1.8292}\right)\right) \tag{31}$$

Model 3: $$0.0161x + 0.4230 = H_0 \left(0.1052\sqrt{DT} + 0.2570\right) \tag{32}$$

Model 4: $$0.0067x + 0.5549 = H_0 \left(0.1867 \ln(DT) + 0.1606\right) \tag{33}$$

Model 5: $$0.0148x + 0.4323 = 9.4469 H_0 \left(1 - \exp\left(-1.6470 f(T_m) DT^{0.3348}\right)\right) \tag{34}$$

Model 6: $$0.0152x + 0.4357 = 8.1402 H_0 \left(1 - \exp\left(-81.3784 \left(\frac{\Delta T^{-0.8555}}{H_0}\right)\right)\right) \tag{35}$$

$$DT = T_{max} - T_{min} \tag{36}$$

$$\Delta T = T_{max} - \frac{\left((T)_{min(i)} + (T)_{min(i+1)}\right)}{2} \tag{37}$$

$$T_m = \frac{\left((T)_{max} + (T)_{min}\right)}{2} \tag{38}$$

$$f(T_m) = 0.017 \exp\left(\exp\left(-0.053\,(T)_{m(i)} \cdot (DT)^{0.3348}\right)\right) \tag{39}$$

Where $x$ is the difference of measured daily temperature, $T_{min}$ and $T_{max}$ are the measured daily minimum and maximum air temperature respectively (in degree Celsius).

### 2.6 Bailek *et al.* model

Bailek *et al.* [14] tested thirty-five empirical models based on clearness index and sunshine duration for constructing the most accurate for estimating the monthly average daily diffuse solar radiation over the Saharan medium. The most accurate model is given below:

$$\left(H_d / H\right) = 0.137 + 0.193\left(S / S_0\right) - 1.244\left(S / S_0\right)^2 \tag{40}$$

## 3. A CASE STUDY

The four town of Algerian big south (Adrar, Tamanrasset, Tindouf and Illizi) are ideal locations to install the solar systems. After reviewing it is clear that there are only two sites in the where the solar radiation is adequately identified, Adrar and Tamanrasset.

The mean objective of this section is to assess the performance of tree commonly applied empirical models that use only sunshine duration for monthly mean daily global solar radiation estimation in Illizi region.

### 3.1 Dataset

Algerian big south regions are a part of the huge northern African Sahara and they characterized by an arid continental climate.

Illizi is facing like the other cities, it has a total area of about 284.61 km$^2$ (figure 1).

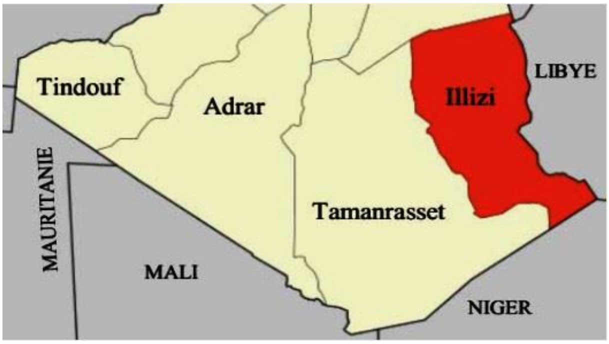


Fig. 1: Geographic position of Illizi

The value of measured data of daily global solar radiation on a horizontal surface and number of sunshine hours in the period of 2007 – 2018 are obtained from the National Meteorological Office (ONM) situated in In Amenas (Latitude North 28°02', Longitude East 9°33', 600 m above the sea level and 239 km from Illizi city).

The mean daily evolution of global solar radiation received on a horizontal surface in the period 2008 - 2014 are shown in figure 2, from which it could be observed that this parameter show fluctuations along the year with the highest values in summer season. The yearly average distribution of global solar radiation is around 3020.95 $MJ/m^2$. This shows that the global solar radiation at Illizi site is higher and many solar applications will have good prospects for achievement.

The measured data during 2007 - 2018 are divided into two periods. The first period (2008 - 2014) was used to develop empirical correlations between the monthly average daily global solar radiation fraction and monthly average sunshine duration fraction, while the second dataset (2015 - 2017 - 2018) are used to validate the correlations.

Data of 2007 and 2016 are used to eliminate faulty data and inexact measurements in the two periods respectively.

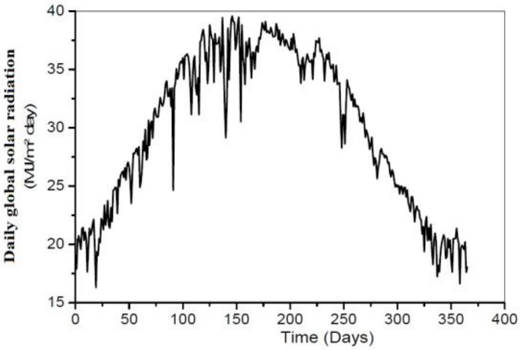


Fig. 2: Daily evolution of global horizontal radiation for the years 2008 - 2014

### 3.2 Sunshine-based models and statistical evaluation

Figure 3 illustrates the correlation between daily global solar radiation and sunshine duration for in Amenas location, Illizi. It is obviously shown that the correlation had the higher coefficient equal to 93 %.

In this study, linear, quadratic and cubic sunshine based models have been selected. The used models are designated on the basis of their performance in different Algerian regions, these models are defined as:

Linear model

$$(H/H_0) = a + b(S/S_0) \tag{41}$$

Quadratic model

$$(H/H_0) = a + b(S/S_0) + c(S/S_0)^2 \tag{42}$$

Cubic model

$$(H/H_0) = a + b(S/S_0) + c(S/S_0)^2 + d(S/S_0)^3 \tag{43}$$

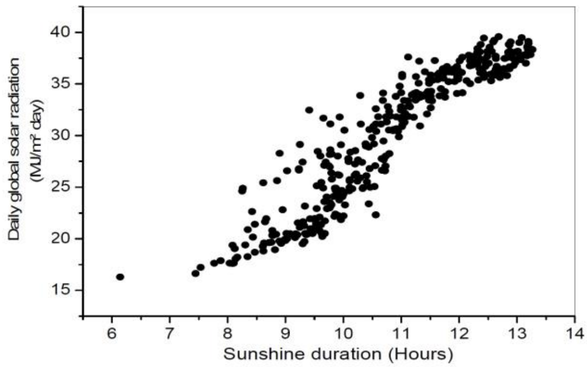


Fig. 3: Correlation between daily global horizontal radiation and sunshine duration for the years 2008-2014

The monthly daily average of five statistical tests, mean bias error ($MBE$), mean absolute bias error ($MABE$), mean percentage error ($MPE$), root mean square error ($RMSE$) and coefficient of determination ($R^2$), have been calculated :

$$MBE = \frac{1}{N}\sum_{i=1}^{N}(H_i - \hat{H}_i) \tag{44}$$

$$MABE = \frac{1}{N}\sum_{i=1}^{N}\left|H_i - \hat{H}_i\right| \tag{45}$$

$$MPE(\%) = \frac{1}{N}\sum_{i=1}^{N}\frac{(H_i - \hat{H}_i)}{H_i} \times 100 \tag{46}$$

$$RMSE = \sqrt{\frac{1}{N}\sum_{i=1}^{N}(H_i - \hat{H}_i)^2} \tag{47)}$$

$$R^2 = 1 - \frac{\sum_{i=1}^{N}(H - \hat{H}_i)^2}{\sum_{i=1}^{N}(\hat{H}_i - \hat{H}_m)^2} \tag{48}$$

Where $H_i$ the i[th] estimated value by the empirical models, $\hat{H}_i$ is the i[th] measured value, $\hat{H}_m$ is the mean measured value and $N$ is the number of observations.

### 3.3 Result and discussion

Newly empirical coefficient the selected models with the values of their coefficients of determination ( $R^2$ ) are presented in **Table 1**.

The analysis of the results shows that all models give a very good fitting between the monthly average daily global radiation and sunshine duration, with $R^2$ higher than 0.99.

**Table 1**: New coefficient of the models

| Models | Values of coefficients | | | | $R^2$ |
|---|---|---|---|---|---|
| | a | b | c | d | |
| **Linear** | 0.83432 | 0.11094 | - | - | 0.99037 |
| **Quadratic** | -9.04644 | 22.0329 | -12.15095 | - | 0.99170 |
| **Cubic** | 41.39485 | -145.67583 | 173.63359 | -68.57197 | 0.99399 |

The models validation was done by comparing the model results and the experimental data of the second period (2015, 2017 and 2018). The series of obtained statistical tests are reported in **Table 2** and a comparison between the developed models results and the experimental data are shown in figure 4.

According to these results, the tree sunshine duration based models gives fairly close results. $RMSE$ varies from 0.51822 to 0.65597, $MBE$, varies from 0.081605 to 0.21197, $MABE$ varies from 0.369839 to 0.50636 and $MPE$ varies from -0.04732 to 0.92104 (negative $MPE$ indicate underestimated values).

**Table 2**: Statistical results for the validation

| Models | $RMSE$ | $MBE$ | $MABE$ | $MPE$ |
|---|---|---|---|---|
| | $MJ/m^2day$ | $MJ/m^2day$ | $MJ/m^2day$ | % |
| **Linear** | 0.65597 | 0.10577 | 0.50636 | 0.92104 |
| **Quadratic** | 0.60878 | 0.081605 | 0.446191 | -0.04732 |
| **Cubic** | 0.51822 | 0.21197 | 0.369839 | 0.64767 |

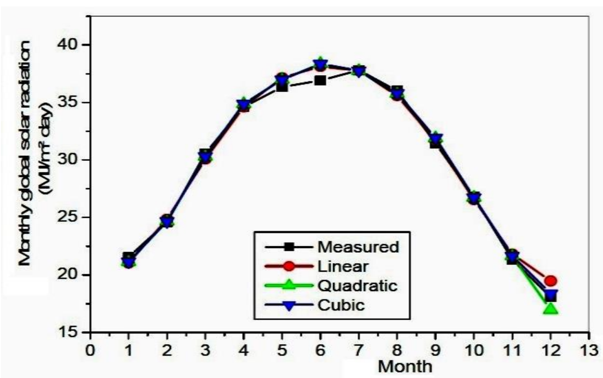


Fig. 4: Comparison between the measured and estimated monthly global horizontal radiation

## 5. CONCLUSION ET PERSPECTIVES

The energy production is in continuous progress in Algeria, the installation of solar power plant offer interesting opportunities for Algeria in order to diversify energy sources especially in the Saharan regions. The prediction of incident solar radiation plays an important role in the design of thermal and photovoltaic solar power systems.

This contribution is divided into two parts; the first one consists in the review of available empirical solar radiation models in Algeria. The review results showed that the empirical sunshine based models are better to use in the prediction of monthly average daily radiation on horizontal surface for Algeria when the measured solar irradiation data exist.

In the second part, linear, quadratic and cubic sunshine based models are used to estimate the monthly mean daily global solar radiation for Illizi town situated in the big south of Algeria. The values produced by these models are then compared with experimental data by means of statistical errors $RMSE$, $MBE$, $MABE$ and $MPE$. The result shows that the designated model revealed accurate results with the lowest statistical errors.

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