Research Article

Development of a Daily Databank of Solar Radiation Components for Moroccan Territory

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The main objective of this work is to create a daily updated database that includes all components of solar radiation, either energetic or spectral radiation. This will lead us to quantify the Moroccan solar potential and to determine the dimensions of all types of solar thermal and photovoltaic systems. Consequently, the obtained database will be the fundamental support for engineers, designers, and all organizations interested in developing solar systems, in different regions throughout Morocco. It will also be a basic tool for researchers in modelling and simulating the new solar systems. Firstly, we used one year's worth of measurements of the different components of the solar radiation, provided by the National Meteorological Department, to establish the extrapolation equations between the global radiation at the reference site and the global radiation of twenty-eight other sites. As well as with the same measurements, we developed the correlation equations between the global solar radiation and the other solar radiation components. Secondly, from ten years of Fez station's daily global radiation measurements and through the extrapolation equations, we were able to estimate the global radiation of all Moroccan cities. Then, by using the obtained global radiation data and the correlation equations, we predicted the other components of solar radiation. Subsequently, with a new measurement campaign carried out on several sites, we validated the estimation models by using the usual statistical indicators. In addition, we compared our results with those obtained by other estimation models. The resulting differences for each solar component display the advantage of our model with errors under 6%. To facilitate the use of our results, we compiled them into maps representing the spread of solar radiation across Morocco.

1. Introduction

The various applications of solar energy developed in recent years have increased the need for solar radiation component data. However, in most cases, there are not enough stations covering the entire country, and the existing stations do not measure all energetic and spectral components of solar radiation.

To remedy this problem, several works using different prediction models have been developed to estimate these solar components around the world. Among these models, we can cite physical models, empirical models [1–3], artificial neural network models [4–7], hybrid

models using a combination of several methods [8, 9], and the models based on the satellite images data [10, 11]. Thus, the physical models are based on physical parameters, which estimates the global radiation from insolation duration [12, 13], meteorological variables [14, 15], and spatial variables [16] in different sky conditions [17, 18]. Also, this model predicts the diffuse solar radiation [19] from the global radiation [20], the insolation duration [21], or the clarity index [22, 23] in different climatic zones [21] and in different sky conditions [24, 25]. However, the same parameters have been used to predict the direct [26], inclined [27] solar radiation and spectral solar components [28, 29].

TABLE 1: Linear models for estimating daily global solar radiation.

Estimation models	Equations	R	Regions
Lemmini's model [32]	$K_t = 0.25 + 0.49 \sigma$	0.92	Beni-Mellal, Morocco
Bargach's model [31]	$K_t = 0.27 + 0.5 \sigma$	0.9	Rabat, Morocco
Nfaoui's model [33]	$K_t = 0.26 + 0.52 \sigma$	0.93	Rabat, Morocco
Zou et al.'s model [7]	$K_t = 0.208 + 0.559 \sigma$	0.91	Tengchong, China

TABLE 2: Quadratic and cubic models for estimating daily global solar radiation.

Estimation models	Equations	R	Region
Ben Kaddour's model [34]	$K_t = 0.18 + 0.83 \sigma - 0.31 \sigma^2$	0.93	Casablanca, Morocco
Zou et al.'s model [7]	$K_t = 0.185 + 0.587 \sigma + 0.037 \sigma^2 - 0.032 \sigma^3$	0.93	Aletai, China

This work aims at establishing a solar data bank of energetic components (H_j , H_{bj} , H_{dj} , and $H_{\beta j}$) and spectral components (H_{UVT} , H_{PAR} , and H_{IR}) all over Morocco. However, this work will be completed in two main steps as follows:

- (i) First step: we will establish the extrapolation equations to estimate the global solar radiation. Then, we will develop the correlation equations to estimate the other solar radiation components
- (ii) Second step: we will use the obtained extrapolation equations to generate the global solar radiation for twenty-eight sites from reference station data. Then, we will bring together the correlation equations and the estimated global radiation to generate the solar energetic and solar spectral component

The obtained results will be subject to a validity test, by comparing them with the measurements collected in available stations. In addition, we will compare our results with those obtained by other estimation models [7, 30–34].

Finally, all results will be presented in maps [35–38] showing all over Morocco.

2. Review of Solar Component Estimation Models

All solar energy conversion systems require knowledge of the solar radiation component measurements. However, in most cases, these measures are not available. For this reason, several studies have been carried out for estimating the components of solar radiation from different variables such as the duration of insolation, the fraction of insolation, and the coefficient of clarity.

2.1. Global Solar Radiation Estimation Models. The simplest model for estimating solar radiation is the linear model developed by Angstrom and after revised by Prescott. This model establishes a direct relationship between the global solar radiation and the insolation fraction [39].

The Angstrom-Prescott model is as follows:

$$K_t = a + b \sigma, \quad (1)$$

where a and b are empirically determined regression constants.

Based on the linear model, several studies have been performed to predict global solar radiation. Among these models, we can cite the models in Table 1.

Other models have been developed such as the quadratic model and cubic model. Among these models, we can mention the models in Table 2.

2.2. Diffuse Solar Radiation Estimation Models. The value of diffuse solar radiation constitute an important data in the study of solar conversion systems. However, several works have focused on the prediction of this component and this by using different variables such as the clarity index K_t . Among these works, we found the following:

- (i) Ben Kaddour's model [34]

$$K_d = 0.961 + 0.456 K_t - 3.344 K_t^2 + 1.67 K_t^3 \quad (2)$$

- (ii) Nfaoui's model [33]

$$K_d = \begin{cases} 0.98, & K_t < 0.1, \\ -1.48 K_t^2 + 0.15 K_t + 0.98, & K_t \geq 0.1, \end{cases}$$

$$R = 0.93 \quad (3)$$

- (iii) Wang et al.'s model, Injinagui, China [25]

$$K_d = 14.7924 K_t^4 - 23.95 K_t^3 + 11.1612 K_t^2 - 2.4767 K_t + 1.1665,$$

$$R = 0.88 \quad (4)$$

3. Data Description

3.1. Used Data. The Laboratory of Solar Energy and the Environment (LESE) of Mohammed V University of Rabat, Morocco, has, since 2008, a network of five

TABLE 3: The geographical data of the measuring stations' locations [40].

Measuring station	Latitude (°) Φ	Longitude (°) λ	Altitude (m)
Agadir	30.38	-9.57	18
Al-Hoceima	35.18	-3.83	12
Beni-Mellal	32.37	-6.4	468
Bouarfa	32.52	-1.95	1100
Casa	33.57	-7.67	56
Dakhla	23.77	-15.93	10
El Jadida	33.23	-8.52	27
Essaouira	31.52	-9.78	7
Ifran	33.5	-5.17	1663
Kenitra	34.3	-6.6	5
Laayoun	27.17	-13.22	63
Larache	35.18	-6.13	46
Marrakech	31.62	-8.03	463
Meknes	33.88	-5.53	548
Midelt	32.68	-4.73	1508
Nador	35.15	-2.92	7
Nousar	33.37	-7.57	200
Ouarzazate	30.93	-6.9	1136
Oujda	34.78	-1.93	465
Errachidia	31.93	-4.4	1037
Safi	32.28	-9.23	43
Sidi Ifni	29.37	-10.18	49
Sidi Sliman	34.23	-6.05	51
Tangier	35.72	-5.75	15
Tantan	28.6	-11.08	229
Taza	34.22	-4	509
Tetouan	35.57	-5.33	5
Rabat	34	-6.83	75

measuring stations installed in Rabat, Fez, Tangier, Tetouan, and Marrakech. These stations measure all components of solar radiation and climatic variables such as the following:

- (i) Energy components: global, diffuse, and direct solar radiation, as well as the overall inclined plane
- (ii) Spectral components: ultraviolet, infrared, and synthetically active light solar radiation
- (iii) Climatic variables: ambient temperature, relative humidity, wind speed, wind direction, and precipitation

In addition to these measures, the National Meteorological Department has made available to us one year of climatic variables and solar component measurements for 29 stations of the national network.

Table 3 represents the geographical data of the measuring stations' locations.

3.2. *Acquisition of Data.* For each station, the following instruments record the measurements of the different components of the solar radiation [41]:

- (i) The Kipp & Zonen brand SP-Lite pyranometer for global solar radiation measurements (2% accuracy). The same type of instrument was used to measure the diffuse radiation, but with a sun visor strip to hide the direct radiation
- (ii) Pyrliometer mounted on a follower type Eppley model NIP 31820 E6 to measure direct solar radiation (accuracy 0.5%)
- (iii) Total Ultraviolet Radiometer (TUVB) model, type Eppley for measuring the total solar ultraviolet radiation (accuracy 2%)
- (iv) Radiometer model NIP 31820 E6, type Eppley, for the measurement of radiation infrared (precision 0.5%)
- (v) Quantum sensor SKP215, type Campbell Scientific for the measurement of photosynthetically active radiation PAR (accuracy 0.5%)
- (vi) Anemometer equipped with a wind vane model wind monitor 05103, type Campbell Scientific, for the measurement of wind speed and direction (accuracy 0.25%)
- (vii) Temperature and relative Humidity Probe HMP45C, manufactured for Campbell Scientific by Vaisala (temperature accuracy 0.2%, humidity accuracy 1%)
- (viii) Rain Gauge ARG100, manufactured by Environmental Measurements for Campbell Scientific, to measure precipitation (accuracy 4%)

3.3. *Storing Data.* All instruments mentioned before are connected to a data acquisition unit (CR10X) with a storage module. Using a computer program, we integrate the measurements collected every 5 seconds over an hour. The obtained hourly values are stored in the raw data files. Then the raw data files are processed and tested to detect and eliminate erroneous values and replace some missing values. In the end, the hourly values are integrated to obtain the daily values.

3.4. *Characteristics and Description of the Reference Site.* The Fez station has been selected as a reference site because of its central geographical location. This city is known as the cultural capital of Morocco (33° 56'N, Longitude 4° 99'W, elevation 579 m) characterized by a seasonal climate, cold and rainy during winter, dry and warm during summer, and mild during spring and autumn [42].

The radiometric station was placed at the top of the Faculty of Science and Technology of Fez's building. The site of the station is completely clear of any shadow effect.

Statistical analysis of this station's data shows a very small percentage of missing or erroneous data (15 erroneous or

TABLE 4: The equations used for the global radiation extrapolation in Morocco.

Site	a_{site}	b_{site}	R^2
Agadir	0.79	994	0.89
Al-Hoceima	0.94	-181	0.85
Beni-Mellal	0.94	409	0.8
Bouarfa	0.81	780	0.8
Casa	0.91	322	0.82
Dakhla	0.7	1907	0.84
El Jadida	0.95	50	0.89
Essaouira	0.89	539	0.83
Ifran	0.97	-52	0.83
Kenitra	0.97	-15	0.83
Laayoun	0.8	1285	0.85
Larache	1.01	-383	0.87
Marrakech	0.9	672	0.84
Meknes	0.95	-14	0.85
Midelt	0.85	740	0.81
Nador	0.95	-214	0.85
Nousar	0.95	92	0.86
Ouarzazate	0.85	1151	0.83
Oujda	0.96	-81	0.79
Errachidia	0.76	1372	0.78
Safi	0.96	214	0.78
Sidi Ifni	0.63	1341	0.78
Sidi Sliman	0.96	-75	0.85
Tangier	0.97	-114	0.81
Tantan	0.65	1534	0.77
Taza	0.94	-29	0.85
Tetouan	1	429	0.83
Rabat	1.03	-317	0.93

missing values over 250 390 measured values or 0.006%) throughout the 10-year measurement period (2009-2018).

4. Presentation of the Method

This work aims at establishing a solar data bank of energetic components (H_j , H_{bj} , H_{dj} , and $H_{\beta j}$) and spectral components (H_{UVT} , H_{PAR} , and H_{IR}) all over Morocco. However, this work will be completed in two main steps: firstly, we used one year's worth of measurements of the different components of the solar radiation, provided by the National Meteorological Department, to establish the extrapolation equations between Fez's global radiation and the global radiation of twenty-eight other sites. As well as with the same measurements, for each sites, we developed the correlation equations between the global solar radiation and the other solar radiation components. Secondly, from ten years of Fez station's daily global radiation measurements and through the extrapolation equations, we were able to estimate the global radiation of all Moroccan cities. Then, by using the obtained global radiation data and the correlation equations,

TABLE 5: Correlation equations for the daily values of the spectral components of solar radiation (Wh/m^2) in function of global solar radiation H (Wh/m^2) for the three sky conditions.

Clarity index intervals	Correlation equations	R^2
$K_t \leq 0.35$	$H_{\text{uv}} = 0.048 H$	0.97
	$H_{\text{PAR}} = 0.488 H$	0.99
	$H_{\text{IR}} = 0.46 H$	0.99
$0.35 < K_t \leq 0.65$	$H_{\text{uv}} = 0.044 H$	0.97
	$H_{\text{PAR}} = 0.484 H$	0.99
	$H_{\text{IR}} = 0.471 H$	0.99
$K_t > 0.65$	$H_{\text{uv}} = 0.04 H$	0.98
	$H_{\text{PAR}} = 0.478 H$	0.99
	$H_{\text{IR}} = 0.478 H$	0.99

TABLE 6: The performance of models used to estimate daily solar irradiation for the Rabat site.

	RMBE	Mean difference	MAPE	RMSE	Number of values
Global radiation	5.42	252	12.14	14.88	290
Diffuse radiation	-3.63	-77	12.71	15.82	257
Direct radiation	1.45	21.6	14.68	17.52	234
Inclined radiation	-6.21	-365	6.35	7.46	323

we predicted the other components of solar radiation (H_j , H_{bj} , H_{dj} , $H_{\beta j}$, H_{UVT} , H_{PAR} , and H_{IR}).

Thus, we have been able to build a database of different components of solar radiation over ten years for the 29 Moroccan sites. In the end, all the obtained results were tested and validated by using a new series of measurements carried out on the five mentioned stations.

5. Extrapolation and Correlation Equations for Daily Solar Components

5.1. Extrapolation of the Daily Global Solar Irradiation. The estimation of global solar radiation can be effected by using several methods, such as the empirical model, ANN model, and satellite imagery. However, the use of these models requires knowledge of several variables and the availability of a database that spans several years. On the other hand, databases are not often available, especially for isolated sites. As a result, to remedy this problem, we developed, as part of this work, an extrapolation method to estimate the global solar radiation. Primarily, this method consists of estimating the global radiation at site where we do not have measurements, from the global radiation measured at another site.

In the first step of this method, from one year of measurements of global radiation for all Moroccan sites, we looked for to establish correlation equations between the global radiation of the different sites and the global radiation of

FIGURE 1: Comparison between measured and estimated values of global radiation.

FIGURE 2: Comparison between measured and estimated values of diffuse radiation using the Collares-Pereira and Rabl's model.

the reference site. For this, we plotted the global radiation values for each site (H_j) according to the global radiation values of Fez's site (H_f), chosen as a reference site.

The obtained shape of the cloud point led us to linear correlations of the type:

$$H_j = a_{\text{site}} H_f + b_{\text{site}}. \quad (5)$$

The coefficients of correlations a_{site} and b_{site} depend strongly on the geographical coordinates of the site and the

status of the atmosphere [43]. Table 4 gathers the obtained values from these coefficients for all Moroccan sites.

5.2. Daily Diffuse Solar Irradiation Estimation. The diffuse component is an important factor for evaluating the performance of solar thermal or solar photovoltaic systems. However, several models, involving the clearness index $K_t = (H_j/H_0)$ [44], have been made to estimate this component. Among these models, we can cite the Ruth and Chant's model, the Collares-Pereira and Rabl's model, and the Liu and Jordan model [45].

FIGURE 3: Comparison between measured and estimated direct radiation values.

To find the valid model for Morocco, we compared the estimated diffuse by the mentioned models with the measured diffuse. Then we concluded that the Collares-Pereira and Rabl's model is the most adequate because it produces a minimal error that does not exceed 5%. This model is illustrated by the following equations [42]:

$$K_d = \begin{cases} 0.99; K_t < 0.17, \\ 14.648 K_t^4 - 21.856 K_t^3 + 9.473 K_t^2 - 2.272 K_t + 1.188; 0.17 \leq K_t \leq 0.8. \end{cases} \quad (6)$$

Knowing the diffuse solar irradiation, the direct solar irradiation can easily be inferred by the following equation [46]:

$$H_{bj} = H_j - H_{dj}. \quad (7)$$

5.3. Estimation of Daily Global Solar Irradiations on an Inclined Plane. The solar flux received by an inclined surface consists of three components: a direct component from the solar disk, a diffuse component from the entire celestial vault, and a component reflected by the surrounding soil.

The estimation of the direct component is completed by simple geometric transposition of the direct irradiation of a horizontal plane H_{bj} . On the other hand, for the diffuse component, several models have been proposed for its estimation [45, 47, 48]. Consequently, an earlier study showed that the isotropic model of Liu and Jordan is the most valid for our sites [49]. Most of the cases, the reflected component is the lowest of the three components, and it is generally assumed isotropic.

TABLE 7: Errors obtained according to clarity index using Rabat measurements.

	H_{UVT} relative error (%)	H_{PAR} relative error (%)	H_{IR} relative error (%)
$K_t < 0.35$	3.8	2.4	2.2
$0.35 < K_t \leq 0.65$	1.0	1.8	2.1
$K_t > 0.65$	1.0	1.1	1.1

The general expression of the inclined daily global solar irradiation with an angle β is given by [49]:

$$H_{\beta j} = \underbrace{R_b H_{bj}}_{\text{direct}} + \underbrace{H_{dj} \frac{1 + \cos(\beta)}{2}}_{\text{diffuse}} + \underbrace{\rho H \frac{1 - \cos(\beta)}{2}}_{\text{reflected}}. \quad (8)$$

R_b is the transposition factor of the direct radiation from a horizontal plane to an inclined plane. It was calculated for a south-oriented plane, by the equation as follows:

$$R_b = \frac{\cos(\delta_j) \cdot \cos(\varphi - \beta) \cdot \sin(\omega_{j\beta}) + \omega_{j\beta} \cdot \sin(\delta_j) \cdot \sin(\varphi - \beta)}{\cos(\delta_j) \cdot \cos(\varphi) \cdot \sin(\omega_j) + \omega_j \cdot \sin(\delta_j) \cdot \sin(\varphi)},$$

$$\omega_{j\beta} = \min \{ \arccos(-\tan(\delta_j) \cdot \tan(\varphi)), \arccos(-\tan(\delta_j) \cdot \tan(\varphi - \beta)) \}, \quad (9)$$

where $\omega_{j\beta}$ is the time angle of the sunset on the inclined plane.

The values taken by the tilt angle β , correspond to the characteristic inclinations relative to the latitude of each site: $\beta = \varphi$, $\beta = \varphi + 20$, $\beta = \varphi - 20$, and $\beta = 90$ corresponding to the vertical facades.

5.4. Estimation of the Spectral Components of Solar Radiation. Some applications of solar energy require knowledge of the

FIGURE 4: Flowchart of the building steps of the daily solar data bank for Morocco.

TABLE 8: Sample data file resulting from different estimations.

Year	Nj (day)	Global	Diffuse	Direct	Inclined ($\varphi+20$)	Inclined ($\varphi-20$)	Inclined (φ)	Inclined (90)	H_{UVT}	H_{PAR}	H_{IR}
2011	1	2808.4	1164.7	1643.7	4683.6	3552.5	4375	4171.9	123.6	1359.3	1322.8
2011	2	2766.6	1202.5	1564.1	4526.3	3470.8	4246.2	4015.1	121.7	1339	1303.1
2011	3	2435.5	1396.1	1039.4	3499.8	2894.4	3383.5	3018.3	107.2	1178.8	1147.1
2011	4	2515.6	1368.7	1146.9	3710.5	3021.7	3565.1	3217.8	110.7	1217.6	1184.8
2011	5	2629.9	1318.1	1311.8	4028	3208.8	3836.5	3520.3	115.7	1272.9	1238.7
2011	6	2844.2	1192.5	1651.7	4669	3574.9	4378.7	4136.5	125.1	1376.6	1339.6
2011	7	2396	1444.7	951.3	3314.2	2805.5	3235.5	2827.6	105.4	1159.7	1128.5
2011	8	2797.1	1250	1547.1	4458.7	3472.3	4209.8	3922.6	123.1	1353.8	1317.4
2011	9	2608.6	1375	1233.6	3860	3139.2	3708	3341.1	114.8	1262.6	1228.7
2011	10	3083.6	1077.5	2006.1	5291.3	3954.6	4918.1	4715.2	135.7	1492.5	1452.4
2011	11	3201.2	1010.7	2190.5	5617.9	4147.9	5198.1	5022.8	128	1530.2	1530.2
2011	12	2695.6	1368.1	1327.5	4022.1	3256.3	3857.7	3480.8	118.6	1304.7	1269.6
2011	13	3228.4	1024.4	2204	5613.5	4167.3	5206	5002.4	129.1	1543.2	1543.2
2011	14	3130.4	1110.8	2019.6	5265.8	3982.2	4918.6	4660.2	137.7	1515.1	1474.4
2011	15	3253.6	1042.2	2211.4	5595.9	4181	5203.6	4967.9	130.1	1555.2	1555.2
2011	16	3160.8	1126.4	2034.4	5264.7	4005	4930	4642.1	139.1	1529.8	1488.7
2011	17	2880.3	1341.1	1539.2	4373.3	3507.7	4181.2	3783.1	126.7	1394.1	1356.6
2011	18	3239.3	1114.8	2124.5	5395.9	4106.4	5055	4748.2	142.5	1567.8	1525.7
2011	19	2272.2	1593.9	678.3	2748	2531.8	2782.5	2248.4	100	1099.7	1070.2
2011	20	3094.1	1268.5	1825.6	4850.4	3821.8	4606.8	4210.1	136.1	1497.5	1457.3
2011	21	3321.7	1132	2189.7	5464.3	4190.8	5136.6	4781.2	146.2	1607.7	1564.5

FIGURE 5: Maps of the monthly average values of daily global irradiancies on a horizontal plane, coming from Morocco. Maps of global solar radiation on a horizontal plane (a–d).

spectral components of solar radiation, namely, the ultraviolet component (H_{UVT}) which is involved in the study of the atmosphere and the variations in the ozone layer thickness.

The photosynthetically active component noted as H_{PAR} (photosynthetically active radiation) intervenes during the photosynthesis process and plant development; knowing the

FIGURE 6: Map of annual cumulation of daily global irradiations on a horizontal plane incident in the Moroccan territory. Map of global solar radiation on a horizontal plane.

H_{PAR} value at various sites allows for the appropriate choice of adapted crops. Lastly, the infrared component H_{IR} is used by satellite techniques to determine the total atmospheric column of the water vapor used by meteorology for the climate prediction [50].

Based on one year's worth of measurements of the different components of the solar radiation provided by the National Meteorological Department, we noticed that the variations of the global radiation and the spectral components, functioning in time, have the same rate. As a result, we searched correlation equations connecting the global solar radiation to the spectral solar radiation.

For this, we graphed each spectral component according to the global radiation, which gave us linear equations of the form $y = ax$. To improve the correlation coefficients, we defined three intervals according to the meteorological state of the day characterized by its clearness index K_t [51]. The results are presented in Table 5.

6. Performance Evaluation and Model Validation

To evaluate the quality of the models used to estimate the solar radiation components, we compared the estimated

values generated by the different models against the measured values by using the usual statistical indicators such as the relative error (RMBE), the mean absolute error (MAE), the mean absolute percentage error (MAPE), and the mean squared error (RMSE) [34, 38].

$$\begin{aligned}
 RMBE &= 100 \frac{\sum_{i=0}^n (p_i - m_i)}{\sum_{i=0}^n m_i}, \\
 MAE &= \frac{\sum_{i=0}^n |p_i - m_i|}{N}, \\
 MAPE &= \frac{1}{N} \sum_{i=0}^n \left| \frac{p_i - m_i}{m_i} * 100 \right|, \\
 RMSE &= \frac{100}{\bar{m}} \sqrt{\frac{\sum_{i=0}^n (p_i - m_i)^2}{N}}.
 \end{aligned} \tag{10}$$

6.1. Validation of Energy Component Models. Using the measurements provided by the Solar Energy and Environment Laboratory's station network, we were able to calculate the statistical indicator and validate the estimation models. However, these calculations were effected

FIGURE 7: Maps of the monthly average values of daily diffuse irradiances on a horizontal incident plane in Morocco. Maps of diffuse solar radiation on a horizontal plane (a–d).

for all sites previously mentioned. Table 6 and Figures 1–3 are examples of the obtained results for the Rabat Site.

6.2. Validating Spectral Components. The formulas for estimating the spectral components of solar radiation from the measurement of global solar radiation were developed

FIGURE 8: Map of annual cumulation of daily diffuse irradiances on a horizontal plane incident in the Moroccan territory. Map of diffuse solar radiation on a horizontal plane.

according to the state of the day characterized by its K_t clarity index. The results in Table 7 revealed that the proposed models estimate the spectral components with remarkable accuracy since the maximum deviations obtained do not exceed 4%.

For all obtained equations, we found that the conditions of the sky (overcast, moderately covered, and clear) have a significant influence mainly on the H_{UV}/H_j fraction. This result is similarly found to the one in Brazil [52]. An estimate of the ultraviolet component that ignores the state of the sky can induce an error of up to 10%. However, the H_{PAR}/H_j and H_{IR}/H_j fractions are less influenced by cloud cover.

7. Application: Building a Ten-Year Database

After having established and validated the extrapolation and correlation equations, we applied them to estimate the different solar radiation components for the different Moroccan sites. The obtained results constitute a solar data bank for all over Morocco for ten years.

Figure 4 represents the flow-chart summarizing all the steps followed for generating all solar components from the site of the Fez.

8. Representative Year

In preproject studies that aimed at sizing solar systems or characterizing the solar radiation potential, it is often necessary to have a minimum of data. Therefore, it is essential to compact the database. Consequently, after having established, for each site, a database for ten years, we were obliged to select a representative year of this database for facilitating the database exploitation.

To determine the representative year, we proceed as follows: for the ten years of estimated values, we calculated an average year. Then, this average year is successively compared to each one of the ten years of estimated values. Consequently, the year with the minimum difference is selected as the representative year.

This work was done for all sites and led us to select 2011 as the representative year for the period between 2009 and 2018.

9. Results

After having established and validated the various components of solar radiation, we created a solar data bank for all over Morocco. Thus, for each city, the obtained results

FIGURE 9: Maps of the monthly average daily direct irradiation in the Moroccan territory. Maps of direct solar radiation on a horizontal plane (a–d).

FIGURE 10: Map of annual cumulation of daily direct irradiations on a horizontal plane incident in the Moroccan territory. Map of direct solar radiation on a horizontal plane.

were grouped in two files easily usable; the first one contains the solar components over ten years between 2009 and 2018, and the second contains the solar components of the representative year. However, this second file has the advantage of providing the maximum of climatic information on a site with a minimum of data. This type of file is requested especially for the preliminary project studies.

Table 8 represents a sample data file resulting from different estimations.

In addition, to give an overall view of the results, we projected the obtained values of the solar irradiations on the Moroccan map. Furthermore, In order to reduce the number of figures, we chose to represent only the monthly averages of the daily values of the midseason month of the representative year. Thus, for all cities, we obtained twenty-three maps that gather the various solar irradiations. As a result, for each of the four solar components (global, direct, diffuse, and inclined), we have five maps; four of them represent seasonal values and the last one represent the annual cumulative values. The obtained maps are shown in Figures 5–12. The three spectral components (H_{UVT} , H_{PAR} , and H_{IR}) are shown in Figure 13.

Finally, in order to evaluate the variation of solar radiation components, we calculated, for each solar component,

the monthly averages of the daily values (Table 9) and the minimum (Table 10) and maximum (Table 11) daily values for each month of the representative year. Caused by the large number of stations, only the results obtained in Rabat's station are presented in Tables 9–11 (minimum, maximum, and averages of the daily values for each month of the representative year).

10. Discussion

From the obtained results in Tables 6 and 7 and the curves in Figures 1–3, we can conclude that the correlation between the estimated and measured solar energy resources has a good level of precision. This was reflected in the following observations:

- (i) The annual average of daily relative errors for energetic components of solar radiation does not exceed 5.42% for global radiation, -3.63% for diffuse radiation, and 2.32% for direct radiation
- (ii) The comparative curves show that the measured and estimated values of solar radiation undergo almost the same variations throughout the year and the differences that do not exceed 12.14% for global

FIGURE 11: Maps of the monthly average values of the daily global irradiations on inclined planes (β = the site latitude). Maps of the global solar radiation inclined with β = the latitude's site (a-d).

FIGURE 12: Map of annual cumulation of daily global irradiances on inclined planes (β = the site latitude) incident in the Moroccan territory. Map of the global solar radiation inclined with β = the latitude's site.

radiation, 12.71% for diffuse radiation, and 17% for direct radiation. This result is approved by comparing the cloud of points generated by representing the estimated values in function of the measured values, with the first bisector, which gave almost identical trends

- (iii) For the spectral components, the relative errors do not exceed 3.8% for H_{UVT} , 2.4% for H_{PAR} , and 2.2% for H_{IR}

When we compared our results with those obtained by other authors' models, we noticed that our method diminished the differences between estimated and measured values. In brief, the results of this comparison are shown in Table 12.

Regarding the maps in Figures 5–12, we notice that the Moroccan territory receives a very important sunshine during all seasons. However, there is an unequal distribution of solar resources between regions. This inequality is reflected by maximum values of radiation in the south and south-east regions such as Ouarzazate, Er-Rachidia, Laayoun, and Dakhla and by minimum values of solar radiation in the north regions such as Tangier, Tetouan, and the coastal zone between Agadir and Tan-Tan where there is a microclimate.

In addition, the spectral component maps show a similar distribution compared to the global radiation maps, reflected by intense irradiances in the south and south-east regions and low irradiances in the north and the microclimate zone. The linear aspect of the estimation equations connecting the spectral components to the global radiation explains this result.

11. Conclusion

Through this work, we have been able to create a database that brings together the different components of solar radiation at daily scale over a period of ten years from 2009 to 2018. This database regroups more than one million daily values (1,058,500 values), which divides into 36,500 values for each site.

To create this databank, at first, we developed a model to estimate the different components of the solar radiation, and then we validated this model by comparing the estimated values with the measurements provided by installed stations. As a result, the validity tests showed that our model presents minimal errors that do not exceed 5.42% for global radiation, 3.8% for H_{UVT} , 2.4% for H_{PAR} , and 2.2% for H_{IR} . In addition, we compared our results with those obtained by other

FIGURE 13: Maps of the annual cumulation of daily irradiations of the spectral components of solar radiation (H_{UVT} , H_{PAR} , and H_{IR}) on the horizontal plane incident in the Moroccan territory. Maps of solar radiation spectral components (a–c).

estimation models developed around the world. The results of this comparison showed the advantage to our model with errors do not exceed 6%.

To get the general idea about the solar radiation distribution over all Morocco and considering the large number of data, we chose to present the obtained results in maps. In order to reduce the number of figures, we chose to represent

only the monthly averages of the daily values of the midseason month for the representative year and the annual cumulative solar irradiations for the same year. As a result, twenty-three maps of solar radiation were generated. Consequently, we have been able to complete and to update the various works affected in our laboratory, and we have been able to build a complete, clean, and precise

TABLE 9: Representative year monthly averages of various solar radiation component daily values (Wh/m²).

	H_j	H_{dj}	H_{bj}	$H_{\beta_j} (\beta = \phi + 20)$	$H_{\beta_j} (\beta = \phi - 20)$	$H_{\beta_j} (\beta = \phi)$	$H_{\beta_j} (\beta = 90)$	H_{UVT}	H_{PAR}	H_{IR}
Jan	2552	1302	1250	3772	3072	3627	3252	112	1235	1200
Feb	3881	1471	2409	5271	4556	5223	4247	162	1864	1843
Mar	4493	1966	2527	4718	4848	5075	3273	189	2162	2131
Apr	5382	2401	2981	4704	5511	5409	2822	231	2595	2542
May	5859	2825	3035	4489	5777	5414	2491	251	2825	2769
June	6942	2723	4220	4900	6722	6129	2459	299	3390	3334
Jul	6668	2727	3941	4900	6522	6029	2546	293	3312	3255
Aug	5742	2552	3191	4743	5788	5571	2723	273	3077	3020
Sept	5001	1878	3124	5051	5349	5526	3327	227	2655	2638
Oct	4231	1383	2848	5533	4913	5559	4313	177	2076	2064
Nov	2585	1196	1503	3820	3117	3681	3264	116	1312	1290
Dec	2470	1024	1508	4129	3128	3855	3682	119	1374	1358

TABLE 10: Representative year monthly maximum values.

	H_j	H_{dj}	H_{bj}	$H_{\beta_j} (\beta = \phi + 20)$	$H_{\beta_j} (\beta = \phi - 20)$	$H_{\beta_j} (\beta = \phi)$	$H_{\beta_j} (\beta = 90)$	H_{UVT}	H_{PAR}	H_{IR}
Jan	3322	1635	2211	5618	4191	5206	5023	146	1608	1565
Feb	5050	2044	3759	6730	5919	6743	5481	206	2414	2414
Mar	6463	2786	4797	6837	6940	7249	5021	259	3090	3090
Apr	7253	3273	5212	6370	7360	7257	3695	298	3467	3467
May	8140	3570	6084	5837	7962	7312	2922	326	3891	3891
June	8192	3575	5999	5556	7895	7115	2684	338	3916	3916
Jul	7832	3652	5563	5522	7612	6944	2887	337	3833	3833
Aug	7072	3320	4551	5452	7018	6600	3069	312	3683	3683
Sept	5883	2981	4175	6065	6185	6416	4235	276	3303	3303
Oct	5285	2424	3907	6523	6034	6688	5344	224	2659	2659
Nov	3688	1843	2669	5953	4630	5638	5109	163	1946	1946
Dec	3061	1459	2151	5530	4016	5083	4984	139	1583	1583

TABLE 11: Representative year monthly minimum values.

	H_j	H_{dj}	H_{bj}	$H_{\beta_j} (\beta = \phi + 20)$	$H_{\beta_j} (\beta = \phi - 20)$	$H_{\beta_j} (\beta = \phi)$	$H_{\beta_j} (\beta = 90)$	H_{UVT}	H_{PAR}	H_{IR}
Jan	1176	1011	59	1051	1185	1167	776	56	574	541
Feb	1884	1074	179	1712	1911	1893	1258	90	919	867
Mar	1114	1103	11	936	1103	1061	672	54	544	512
Apr	886	877	9	741	876	842	531	43	432	407
may	1843	1825	18	1536	1821	1747	1099	89	900	848
June	3303	2193	316	2693	3254	3101	1856	159	1612	1519
Jul	4885	2052	2109	3620	4758	4403	2039	138	1407	1327
Aug	3996	1815	833	3346	3986	3840	2201	173	1904	1853
Sept	2418	1563	171	2265	2494	2502	1592	89	900	848
Oct	2778	801	823	3052	3003	3189	2371	39	395	372
Nov	931	397	315	734	1049	1003	411	19	196	184
Dec	679	616	1	659	702	712	359	30	304	286

TABLE 12: Relative errors (RMBE) calculated from the values generated by different methods of estimation and the measured values.

Solar components	Our estimation methods	Nfaoui's methods	Lemmini's methods	Bargach's methods	Benkaddour's methods	Zou et al.'s model	Wang et al.'s model
Global solar radiation	5.42%	-11%	-14.7%	-10.6%	14.13%	-17%	
Diffuse solar radiation	-3.63%	12.76%			-8%		11.7%

database covering all Morocco over a period of ten years. This database covers the basic needs of engineers, installers of solar systems, and especially researchers who often need a long-term database.

Nomenclature

H_j :	Daily global solar radiation on horizontal surface (Wh/m ² day)
H_{dj} :	Daily diffuse solar radiation (Wh/m ² day)
$H_{\beta j}$:	Daily global solar radiation on tilted surface (Wh/m ² day)
H_{bj} :	Daily beam solar radiation (Wh/m ² day)
H_f :	Daily global solar radiation of Fez's site (Wh/m ² day)
H_{UVT} :	Daily ultraviolet solar radiation (Wh/m ² day)
H_{PAR} :	Daily photosynthetically active radiation (Wh/m ² day)
H_{IR} :	Daily infrared solar radiation (Wh/m ² day)
H_0 :	Daily extraterrestrial solar irradiation (Wh/m ² day)
I_0 :	Solar constant 1 367 W/m ²
φ :	Latitude of the place (°)
δ :	Solar declination (°)
R^2 :	Correlation coefficient (%)
RMBE:	Relative error (%)
MAE:	Mean absolute error (%)
MAPE:	The mean absolute error percentage (%)
RMSE:	The mean squared error (%)
K_t :	Daily clearness index
K_d :	Daily diffuse fraction
σ :	Insolation fraction.

Data Availability

The data used to support the findings of this study are available from the corresponding author upon request.

Conflicts of Interest

The authors declare that there is no conflict of interest regarding the publication of this paper.

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