# Solar Energy Resource Assessment Using GHI and DNI Satellite Data for Moroccan Climate

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**Abstract.** Solar energy is in rapid development in Morocco. Thanks to its geographical and climatic location, the Kingdom of Morocco is privileged to develop large-scale solar energy exploitation. The knowledge of the solar potential in a given site is crucial for most solar energy applications. The present study aims to evaluate the energy potential in several cities in Morocco to provide guidance to solar energy users about the available amount of energy. The assessment was done using 10 years of data from the Helioclim3 satellite database. In addition to the solar potential analysis, we performed a classification of the days to determine the dominant climatology based on the clear sky index. The results showed the dominance of clear days toward all study sites, and selected sites may be a promising location for solar projects with annual global horizontal irradiation reaching 2075 kWh/$m^2$ and direct normal irradiation reaching 2463 kWh/$m^2$.

**Keywords:** Solar resource assessment · Global horizontal irradiation · Direct normal irradiation · Morocco · HelcioClim3

## 1 Introduction

Energy is a crucial factor for the economic and social development of countries. Energy is at the heart of all sectors, including industry, transport, commerce, agriculture, health, residential, etc. A reliable and sufficient energy supply is necessary to meet the various energy needs and increase productivity. However, fossil energy sources, in addition to being soon exhausted and unsustainable for future development, they present serious threats to the environment. About two-thirds of the world's carbon dioxide ejections come from these fuel sources, whose current share of energy production.

Morocco is the largest net importer of energy in the North African region. Morocco's energy profile has been dominated for a long time by importing its energy resources [1]. The Moroccan energy mix is composed of more than 90% of fossil fuel of the total


R. Saidi et al. (Eds.): ICATH 2021, LNDECT 110, pp. 275–285, 2022.
https://doi.org/10.1007/978-3-030-94188-8_26

primary energy supply and 80% of the electricity supply. To overcome this dependence, the country is making great efforts in developing renewable energy and integrating it into existing and possibly emerging networks. Morocco has launched a plan to increase the share of renewable energy in the energy mix. By 2030 the country has committed to reducing greenhouse gas emissions by 17% from baseline levels and achieving 52% of installed electricity capacity from renewable sources. Currently, the Moroccan energy mix is quite diversified, with a remarkable contribution from renewable sources. In 2018, Morocco installed 3700 MW (1170 MW from hydro, 1220 MW from wind, and 710.8 MW from solar), and is anticipated rising 12.900 MW by 2030, which will be distributed as follows: 3100 MW from hydro, 5000 MW from wind, and 4800 MW from solar [2, 3].

Solar energy is the most plentiful source of energy on the planet [4]. Solar energy can be exploited in several forms: direct conversion into electrical energy by photovoltaic cells; direct conversion into thermal energy by solar thermal collectors; thermodynamic conversion into electrical energy by combining solar thermal collectors, turbines or thermal engines and electrical generators; and conversion into chemical energy by photochemical means [5].

For all these applications, solar radiation is a very important variable. The information on solar radiation is also essential for feasibility study and selection of favorable sites, optimization of the energy produced through accurate forecasting of solar radiation, estimation of the financial cost of any new solar project. The solar resource can be evaluated through meteorological stations installed on the ground and equipped with various sensors. The best accuracy and data quality are obtained through these ground sensors. However, the density of measuring stations is still insufficient due to their high costs [6]. To overcome this lack of weather stations, satellite imagery is used as an alternative approach for solar resource estimation [7].

This study evaluated the solar potential by analyzing two solar components, the global horizontal irradiation (GHI) and the direct normal irradiation (DNI) at nine sites in Morocco. In addition, we performed an analysis of the climatology regarding the clear sky based on the clear sky index calculation $K_t$. For these purposes, irradiation data and typical meteorological years (TMY) from the HelioClim3V5 database were used.

## 2 Study Sites and Data

### 2.1 Study Sites

The Kingdom of Morocco is a country located in northwest Africa geographically and climatically favored to develop large-scale exploitation of renewable energy. Solar energy is considered a promising renewable alternative for Morocco. The country has a strong potential of sunshine with an average of global radiation of about 5.3 kWh/m$^2$/year with an annual insolation duration between 2700 h in the north and up to 3500 h in the south [8]. In this study, we selected several sites in Morocco to evaluate their solar potential. The selected sites are: Benguerir, Erfoud, Missour, Zagora, Tantan, Oujda, Benguerir, Ouarzazate, Oujda, Ain Bni Mathar, and Taza. We selected these sites to cover several locations, including some EnerMENA stations (Erfoud, Missour, Zagora, Tantan, and

Oujda) that were installed in addition to six other stations by the German Aerospace Center (DLR) in the Mena region to assess their solar potential [9].

The map of Fig. 1 represents the geographical location of the study sites, the size of bubbles represents GHI intensity estimated from SolarGIS [10]. Table 1 represents the geographical coordinate and the yearly estimated GHI and DNI. It can be seen that the annual GHI varies between 1876 kWh/m$^2$ and 2157 kWh/m$^2$, and the DNI varies between 1786 kWh/m$^2$ and 2473 kWh/m$^2$. High irradiation intensities are observed at Ouarzazate, Erfoud, Missour, Zagora, and Benguerir.

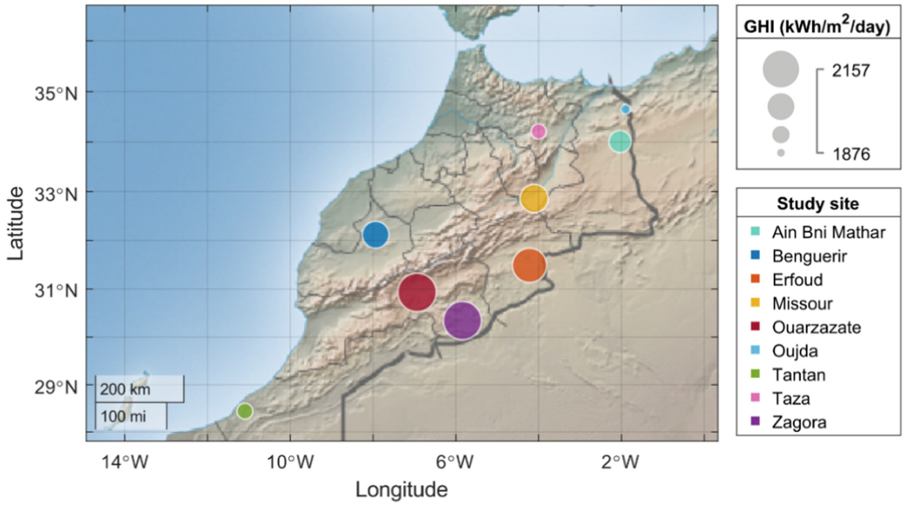


**Fig. 1.** Geographical location of the study sites. The size of the bubbles corresponds to the intensity of the annual average of GHI estimated from SolarGis.

**Table 1.** Geographic information and yearly of GHI and DNI from SolarGis [10].

| Site | Latitude (°) N | Longitude (°) W | Yearly GHI kWh/m$^2$/day | Yearly DNI kWh/m$^2$/day |
|---|---|---|---|---|
| Benguerir | 32.12 | 7.94 | 2004 | 2084 |
| Erfoud | 31.49 | 4.21 | 2098 | 2182 |
| Missour | 32.86 | 4.10 | 2020 | 2189 |
| Zagora | 30.34 | 5.84 | 2154 | 2290 |
| Tantan | 28.43 | 1.09 | 1909 | 1786 |
| Oujda | 34.65 | 1.9 | 1876 | 1930 |
| Ouarzazate | 30.93 | 6.93 | 2157 | 2473 |
| Ain Beni Mathar | 34.00 | 2.03 | 1957 | 2060 |
| Taza | 34.21 | 3.998 | 1904 | 1967 |

To assess the solar resource at different sites, solar radiation data were collected from HelioClim3 (HC3v5) version 5 database via soda portal [11]. For the clear-sky climatology study, we calculated the clear sky index using the clear sky radiation derived from the McClear model. The choice of HelioClim3 and McClear was based on previous validations of these two databases at several stations in Morocco where good performances were obtained [12–14].

HC3 [15] is a database providing records of solar irradiation in the field of view of the Meteosat satellite covering Europe, Africa, the Atlantic Ocean, and the Middle East [16] for different time steps ranging from 1 min to 1 month, from 2004 up to the day before the current day. These data are derived from processing Meteosat satellite images using the Heliosat-2 method [17, 18], that combines a clear sky model with a cloud index.HC3v4 and HC3v5 are two versions of HC3. The HC3v4 version uses the European Solar Radiation Atlas model (ESRA) [19, 20] as a clear sky model with a monthly climatology of the linke turbidity [21] as input, while the HC3v5 [22, 23] is a proposed version to improve HC3v4 by combining it with the clear sky model McClear [24] whose inputs are information on the clear atmosphere content (aerosol properties, the total column content in water vapor and ozone) produced by the Monitoring Atmosphere Composition and Climate Services (MACC) [25].

McClear [24] is a physical model to estimate solar irradiation under clear sky conditions. It exploits atmospheric composition datasets provided by MACC projects such as aerosol partial and total optical depths -AOD- at different wavelengths, total water vapor, and ozone contents. The model provides time series at any location since 2004, with a delay of 2 days, with a temporal resolution up to 1 min (interpolation).

## 3 Solar Resource Assessment

Solar radiation or irradiation is the incident energy received per unit area during a given period (hour or day), measured in kWh/m$^2$ or J/m$^2$. As it passes through the atmosphere, solar radiation interacts with the various components of the atmosphere. The interactions of solar radiation with the Earth's atmosphere result in three fundamental broadband components of interest to solar energy conversion technologies. DNI is the solar irradiation coming directly from the solar disk, not absorbed and not scattered. Its value weakens with the presence of clouds. It is of interest to concentrated solar power (CSP) and concentrated photovoltaic (CPV) technologies. DHI is diffuse horizontal irradiation resulting from the scattering of the irradiation by the atmosphere components, and GHI is the total irradiation incident on a horizontal surface. It is the sum of direct and diffuse irradiation. GHI is interesting for photovoltaic technologies (PV). In this study, we will focus on the analysis of these two components, the GHI and the DNI.

### 3.1 Monthly and Yearly Values

To quantify and evaluate the solar potential for a given location, the calculation and analysis of monthly and yearly values is an approach commonly applied [26, 27]. It allows the evaluation of available solar potential at a given location, and to make comparisons between several sites. To evaluate the solar potential, we used the TMY (Typical

Meteorological Year) generated using 10 years of data from 2011 to 2020. The TMY is a synthetic year of solar and meteorological parameters at an hourly time step which is representative of a meteorological scenario at a given site. Comparison results of monthly averages for GHI and DNI for the nine study sites are shown in Fig. 2 and Fig. 3, respectively. The annual values and monthly averages of daily GHI and DNI for each site are summarized in Table 2 and Table 3, respectively.

The results shown in the tables show that the annual accumulated solar irradiation is significant for all sites. For GHI, annual values of 2075 kWh/m$^2$, 2025 kWh/m$^2$, and 2031 kWh/m$^2$ are obtained for Ouarzazate, Zagora, and Erfoud, respectively. The lowest values are obtained for Oujda with an annual GHI of 1840 kWh/m$^2$ and Tantan with an annual GHI of 1849 kWh/m2. The annual DNI is also important; the most significant values of DNI are also obtained for Ouarzazate, Erfoud, Missour, and Taza, with values of 2436 kWh/m$^2$, 2339 kWh/m$^2$, 2312 kWh/m$^2$ and 2252 kWh/m$^2$. While the lowest annual average in terms of DNI is obtained for Tantan.

According to the analysis of the bar plots of Fig. 2 and Fig. 3, the GHI is more important during the summer compared to other seasons. The high value of GHI is detected in Erfoud during June with a value of 7.6 kWh/m$^2$, Ouarzazate, Taza, and Zagora sites also have high monthly GH values of 7.5 kWh/m$^2$, 7.49 kWh/m$^2$, and 7.43 kWh/m$^2$ respectively. The lowest value of GHI for June was recorded at Tantan with a value of 6.05 kWh/m$^2$. For the whole month the sunniest sites are Ouarzazate, Erfoud, Missour, Zagora, and Benguerir. The sites of Taza, Oujda, and Ain Bni Mathar represent the lowest radiation values of radiation during January, February, October, November, and December.

The monthly averages of DNI are high during all seasons. The maximum values of DNI are recorded at Ouarzazate with values of 7.84 kWh/m$^2$, 7.9 kWh/m$^2$, 7.6 kWh/m$^2$, and 8.12 kWh/m$^2$ in March, April, May, and June, respectively. Benguerir, Missour, Erfoud, and Zagora represent a strong DNI varying between 7.8 kWh/m$^2$ and 4.02 kWh/m$^2$. During summer the lowest DNI was obtained in the Tantan site with a value of 4.39 kWh/m$^2$. Taza, Ain Bni Mathar and Oujda share a similar behavior during the majority of months.

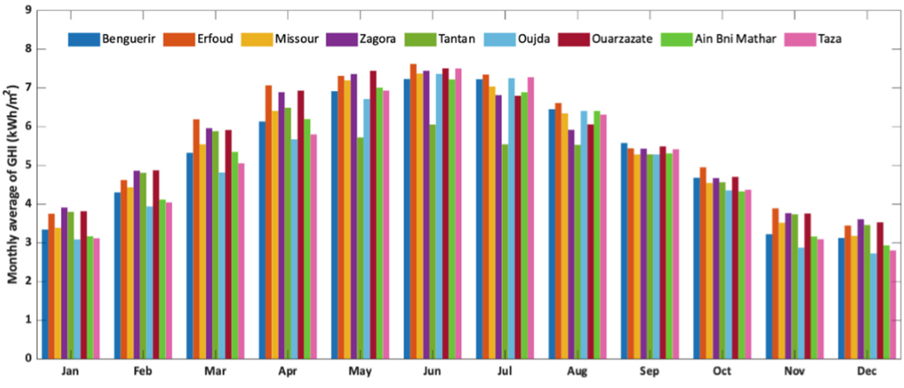


**Fig. 2.** Comparison between the monthly averages of daily GHI (kWh/m2) for all study sites.

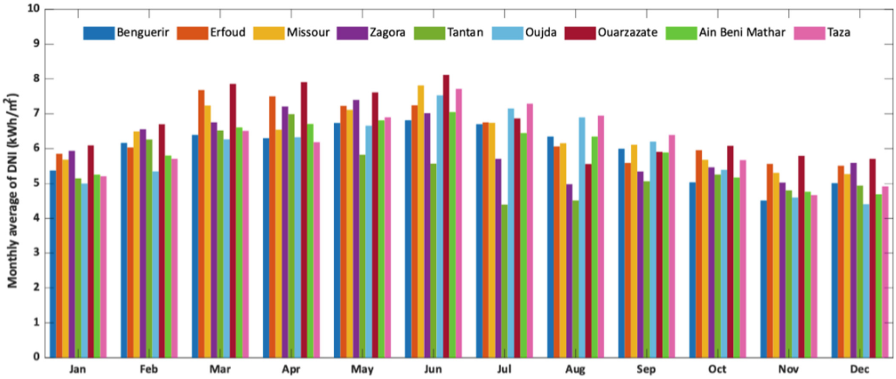


**Fig. 3.** Comparison between the monthly averages of daily DNI (kWh/$m^2$) for all study sites.

**Table 2.** Monthly and annual averages of daily GHI (kWh/$m^2$) for study sites.

| | Bengu-erir | Erfoud | Missour | Zagora | Tantan | Oujda | Ouarz-azate | Ain Bni Mathar | Taza |
|---|---|---|---|---|---|---|---|---|---|
| Jan | 3.34 | 3.75 | 3.38 | 3.91 | 3.79 | 3.08 | 3.81 | 3.16 | 3.11 |
| Feb | 4.30 | 4.62 | 4.43 | 4.86 | 4.81 | 3.94 | 4.87 | 4.11 | 4.04 |
| Mar | 5.32 | 6.18 | 5.54 | 5.96 | 5.88 | 4.81 | 5.91 | 5.34 | 5.05 |
| Apr | 6.13 | 7.06 | 6.40 | 6.88 | 6.48 | 5.67 | 6.92 | 6.19 | 5.80 |
| May | 6.91 | 7.31 | 7.19 | 7.35 | 5.72 | 6.70 | 7.44 | 7.00 | 6.92 |
| Jun | 7.22 | 7.61 | 7.37 | 7.44 | 6.05 | 7.35 | 7.50 | 7.21 | 7.50 |
| Jul | 7.22 | 7.34 | 7.03 | 6.81 | 5.54 | 7.24 | 6.79 | 6.88 | 7.27 |
| Aug | 6.44 | 6.60 | 6.33 | 5.91 | 5.53 | 6.40 | 6.06 | 6.40 | 6.30 |
| Sep | 5.57 | 5.44 | 5.28 | 5.43 | 5.28 | 5.28 | 5.49 | 5.30 | 5.41 |
| Oct | 4.67 | 4.95 | 4.54 | 4.66 | 4.56 | 4.35 | 4.70 | 4.32 | 4.37 |
| Nov | 3.22 | 3.89 | 3.51 | 3.76 | 3.73 | 2.87 | 3.75 | 3.16 | 3.09 |
| Dec | 3.12 | 3.44 | 3.17 | 3.60 | 3.46 | 2.72 | 3.52 | 2.93 | 2.80 |
| Year | 1932 | 2031 | 1953 | 2025 | 1849 | 1840 | 2075 | 1888 | 1877 |

**Table 3.** Monthly and annual averages of daily DNI (kWh/m$^2$) for study sites.

| | Bengu-erir | Erfoud | Missour | Zagora | Tantan | Oujda | Ouarz-azate | Ain Bni Mathar | Taza |
|---|---|---|---|---|---|---|---|---|---|
| Jan | 5.37 | 5.85 | 5.68 | 5.93 | 5.14 | 4.99 | 6.08 | 5.25 | 5.20 |
| Feb | 6.16 | 6.03 | 6.48 | 6.55 | 6.26 | 5.34 | 6.69 | 5.79 | 5.70 |
| Mar | 6.39 | 7.67 | 7.23 | 6.75 | 6.51 | 6.26 | 7.85 | 6.60 | 6.50 |
| Apr | 6.29 | 7.49 | 6.53 | 7.20 | 6.98 | 6.32 | 7.90 | 6.70 | 6.18 |
| May | 6.73 | 7.22 | 7.10 | 7.39 | 5.82 | 6.65 | 7.61 | 6.80 | 6.89 |
| Jun | 6.80 | 7.23 | 7.81 | 7.01 | 5.57 | 7.52 | 8.11 | 7.04 | 7.70 |
| Jul | 6.69 | 6.75 | 6.73 | 5.70 | 4.39 | 7.14 | 6.86 | 6.44 | 7.28 |
| Aug | 6.34 | 6.06 | 6.15 | 4.97 | 4.51 | 6.89 | 5.55 | 6.34 | 6.94 |
| Sep | 5.99 | 5.58 | 6.11 | 5.34 | 5.06 | 6.19 | 5.90 | 5.88 | 6.39 |
| Oct | 5.03 | 5.95 | 5.67 | 5.46 | 5.25 | 5.38 | 6.07 | 5.16 | 5.66 |
| Nov | 4.50 | 5.56 | 5.30 | 5.02 | 4.80 | 4.59 | 5.79 | 4.76 | 4.66 |
| Dec | 5.00 | 5.50 | 5.26 | 5.58 | 4.93 | 4.40 | 5.70 | 4.68 | 4.91 |
| Year | 2167 | 2339 | 2312 | 2215 | 1980 | 2181 | 2436 | 2173 | 2252 |

### 3.2 Daily Average

Another analysis could be performed by analyzing the daily maximum and average components of GHI (Fig. 4) and DNI (Fig. 5) for the Benguerir site as an example. For this site, significant values of irradiance are obtained during the summer season. The maximum and average values of GHI are 1067 w/m$^2$ and 362.16 w/m$^2$ detected during May. DNI values are significant for almost all seasons; the maximum value is obtained during May with a value of 965 w/m$^2$ for an average of 423.41 w/m$^2$.

### 3.3 Clear Sky Characterization

To investigate the distribution of clear days at the study sites, we used the clear sky index (Eq. (1)) defined by the ratio between GHI and the clear sky $GHI_{cls}$ derived from the clear sky model McClear. Figure 5 illustrates the daily distribution of the clear sky index over the period from 2011 to 2020. According to [28, 29] clear days correspond to values of $K_t \geq 0.7$.

$$K_t = \frac{GHI}{GHI_{cls}} \tag{1}$$

It can be seen that the majority of $K_t$ variations are between 0.6 and 0.8. Zagora and Ouarzazate are characterized by the highest percentage of clear days that correspond to 95%. Erfoud, Missour, Ain Bni Mathar, Benguerir, Oujda, Taza, and Tantan also have significant percentages of clear days of 93%, 92%, 90%, 89%, 87%, 86%, and

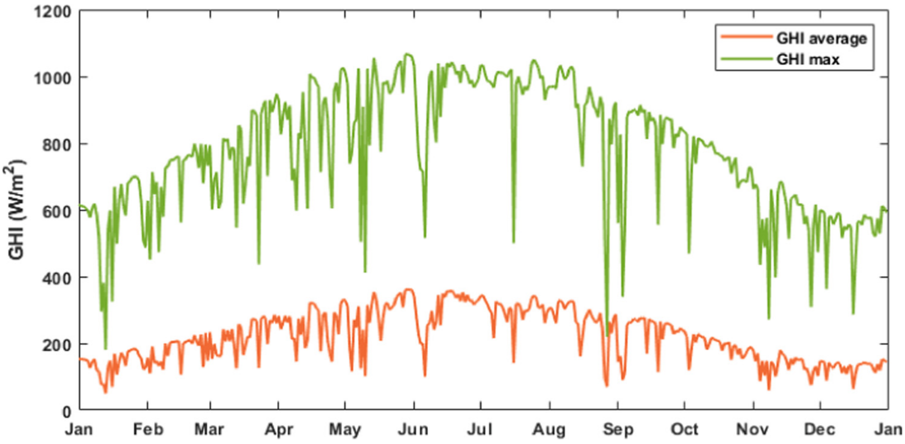


**Fig. 4.** Daily average and maximum of GHI for Benguerir site as an example.

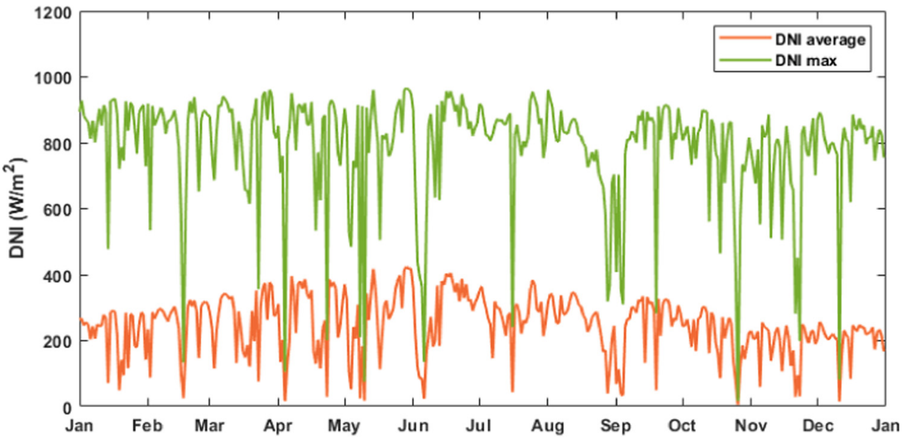


**Fig. 5.** Daily average and maximum of DNI for Benguerir site as an example.

85%, respectively. This justifies the intensity of radiation observed in these sites;indeed, clouds tend to reduce solar irradiation via the phenomenon of absorption and under clear sky conditions the radiation is less attenuated [30] (Fig. 6).

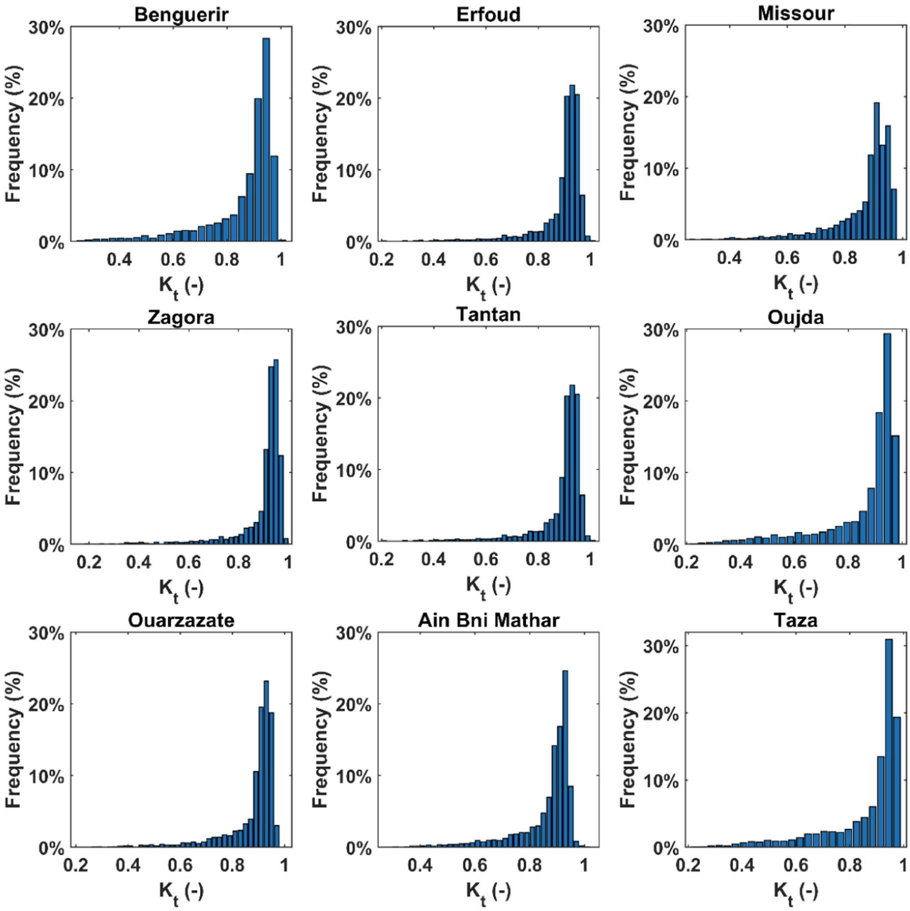


**Fig. 6.** Frequency distribution of clear sky index Kt using HC3 data from 2011 to 2020.

## 4 Conclusion

This study aimed to assess the solar potential of nine sites in Morocco (Benguerir, Erfoud, Missour, Zagora, Tantan, Oujda, Ain Bni Mathar, and Taza) using TMY for GHI and DNI generated using 10 years of data from the HelioClim3 satellite database. The purpose of the analysis is to provide a preliminary insight to engineers and project developers about the solar potential available in various cities in Morocco for solar applications, energy efficiency and feasibility analysis of solar projects either for PV through GHI or CSP through DNI analysis, and also includes an analysis of the prevailing climatology regarding clear sky conditions.

The analysis showed that almost all locations are characterized by the dominance of clear days with percentages that exceed 90% over the analysis period between 2011 and 2020. The sites are characterized by high annual irradiation ranging between 1840 kWh/m$^2$ and 2075 kWh/m$^2$ for GHI and between 1980 kWh/m$^2$ and 2436 kWh/m$^2$ for

DNI. The monthly irradiation is also significant, the monthly evolution of GHI showed that most of the sites are characterized by a high GHI, especially during May, June and July that exceeds 7 kWh/m$^2$, while during these months, the low values of GHI are obtained for Tantan site with values of 6 kWh/m$^2$. For DNI, the highest value of radiation is obtained for the site of Ouarzazate with an average of 8.11 kWh/m$^2$ during June, and the minimum values recorded are 4.3 kWh/m$^2$ for Oujda in December and Tantan during August and July. The results presented in this paper indicate that solar energy at the sites studied is a promising alternative to fossil fuels and these sites could be candidate sites for strategic solar energy projects. Upcoming studies will focus on the assessment of wind resources for wind energy.

**Acknowledgement.** The authors thank the Green Energy Park, research platform by IRESEN (Research Institute in Solar Energy and New Energies). The authors would like to express their gratitude to MINES ParisTech for providing access to the solar irradiation data.

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