



Statistical study of global solar radiation in the Algerian desert: a case study of Adrar town

Ibrahim Oulimar^{1,2} · Kada Bouchouicha³ · Nadjem Bailek¹ · Mebrouk Bellaoui²

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Abstract

This study examined the surface global solar irradiation variability in the southern Algerian region, with regard to the regional climatic and environmental features. The statistical analysis used ground data acquired in measurement stations operated by a technical platoon of meteorologists and physicists at the Renewable Energy Research Unit in the Saharan Environment (URER/MS). A graphical statistical analysis of long-term solar irradiance data is performed using appropriate visualizations, such as time series plots, box plots, and histograms. The data used is that of the decade (2011–2020), and the analysis is extended to the last 30 years (1990–2020) based on solar radiation data handed by the National Aeronautics and Space Administration (NASA). The present study takes advantage of a unique and high-quality dataset consisting of 10 years of concurrent records of global solar irradiation in the South Algerian region. The results of this study pointed out a remarkable variability in seasonal and annual scales and confirmed that this region has enormous solar energy potentiality, where the average periodic diurnal energy for global solar radiation measured on a horizontal plane exceeds 6.16 kWh/m²/day and an additive total energy of 2.2 MWh/m²/time on average.

Keywords Global solar radiation · Measured data · NASA data · Statistical analysis

1 Introduction

Utilizing renewable energy sources is a crucial measure in addressing and minimizing the severe consequences of climate change. Significant evidence has emerged in recent years indicating the remarkable potential for expansion in

the renewable energy sector; in 2020, there was a substantial increase in renewable energy capacity, the renewable energy sources contributed to more than 27.6% of the world's electricity generation (IRENA 2023).

The assessment of the impacts of increasing renewable energy share in the Algerian energy system uses a mixed-integer linear programming approach. This approach has demonstrated that the energy system can successfully transition to a low-carbon system, but challenges such as system reliability, costs, and infrastructure remain (Dokkar et al. 2023).

To meet the electricity demands for domestic, commercial, or industrial purposes, solar energy stands out as the most advantageous renewable energy source due to its numerous benefits. It is readily available and abundant, capable of fulfilling a substantial portion of our energy requirements. Among the various solar technologies available, solar photovoltaic technology is the most recognized and widely adopted option.

In Algeria, there has been a noticeable increase in the development of solar photovoltaic (PV) farm capacities, with the outlook indicating a growing number of solar power projects in the future (Kada Bouchouicha et al. 2021a, b; Guermoui et al. 2021; Hassan et al. 2021; CEREF 2020).

✉ Ibrahim Oulimar
oulimar.brahim@gmail.com
https://urerms.cder.dz/

Kada Bouchouicha
K.bouchouicha@gmail.com

Mebrouk Bellaoui
https://urerms.cder.dz/

¹ Materials and Energies Research Laboratory (MERL), Faculty of Science And Technology, University Amine Elokhal El Hadj Moussa Eg Akhamouk, 11000 Tamanrasset, Algeria

² Unité de Recherche en Energies Renouvelables en Milieu Saharien, URERMS, Centre de Développement des Energies Renouvelables, CDER, 01000 Adrar, Algeria

³ Centre de Développement Des Energies Renouvelables, CDER, BP 62 Route de L'Observatoire, 16340 Bouzaréah, Algiers, Algeria

When choosing a location for such installations, it is vital to take into account multiple factors to enhance the production efficiency of the solar PV farm while keeping project costs in check. Among these factors, the most crucial is the amount of solar radiation a site receives, which significantly influences the farm's effectiveness and financial viability (K. Bouchouicha et al. 2021a, b).

The complexity of solar radiation variability makes it challenging to comprehensively analyze it in both spatial and temporal dimensions. However, advanced analytical techniques, including time series analysis, regression analysis, machine learning algorithms, and spatial analysis methods, can be employed to gain insights into this variability (Goliatt and Yaseen 2023; Upadhyay et al. 2023; El-Kenawy et al. 2022; Keshtegar et al. 2022; Bellaoui et al. 2021). This is essential for more efficient usage of solar energy resources, ultimately facilitating the more effective utilization of solar energy resources (Okono et al. 2022; Torbus et al. 2023; Makade et al. 2021; Salhi et al. 2023).

Numerous research efforts have been conducted to analyze the historical solar energy resources in terms of solar irradiation and sunshine duration data. The primary goal of these studies is to detect persisting trends and identify their driving factors (Nunez and Li 2008; Manara 2019; Friedlingstein et al. 2022). For instance, a study by Katipoğlu (2022) focuses on detecting solar radiation trends, particularly in terms of sunshine duration, along with the consideration of meteorological variables such as seasonal and annual temperature, maximum precipitation, relative humidity, and wind speed. Feng et al. (2021) examine the long-term solar radiation variation trends and spatial patterns in mainland China, presenting a unique viewpoint through the application of an optimized empirical model. In the context of climate change, some studies investigate the influence of climate change on solar irradiance patterns. For example, Zagouras et al. (2013) utilize historical data and climate models to assess how cloud cover and other climatic variables have affected solar irradiance. These studies aim to provide valuable insights into the complex relationship between solar radiation and climate change, which is crucial for understanding and managing energy resources in the face of climate change irradiance (Watanabe et al. 2016).

In this context, the present work provides information and knowledge on the temporal variability of the surface solar irradiation in the southern Algerian region using ground data collected over 10 years from measurement stations operated by a dedicated team of meteorologists and physicists at the Renewable Energy Research Unit in the Saharan Environment (abbreviation in French UREER/MS). It also aimed to investigate the climatological trends in the surface solar radiation data. The present study takes advantage of unique high-quality concurrent records of global solar irradiation in this national territory region. Detailed studies

based on real ground measurements for solar radiation in the Saharan region are rare, due to the lack of specialized radiometric measurement stations (Bouchouicha 2017). The scope of this study is to characterize the variability of the solar radiation in the Algerian desert climate in particular and may serve as an indication of what might be expected in other desert regions of the world.

The composition of a precise radiometric database requires a quality management system, planning, and execution of the main measurement operations based on international standards (Myers 2013; OMM 2011). The research unit in renewable energies in the Saharan environment (UREER/MS) with its scientific vocation in Renewable Energies tries to complete measurement campaigns and installation of high-quality solar radiation measuring devices (Bouchouicha and Oulimar 2013; Oulimar et al. 2022) to meet national needs for information and scientific data on solar energy.

In this contribution, we will present the statistical analysis of the 10-year (2011 – 2020) collected data with different time slices from the small hourly variation to the long-term variation (climatological normal), the selected measurements related to global radiation assessment collected at the UREER-MS site situated at a latitude of 27.52° N and a longitude of 0.18° W, with an elevation of 292 m above sea level (Kada Bouchouicha et al. 2019; 2018). Due to the lack of good-quality long-term solar irradiance measurements corresponding to a 30-year climatological period according to the latest WMO guidelines (OMM 2017), and in order to expand the analysis of time series data by the standard climatological normal for the most recent 30-year period, a second set of data used is MERRA-2 (Modern Era Retrospective Analysis for Research and Application) data set (available at <http://gmao.gsfc.nasa.gov/reanalysis/MERRA-2>) and is provided by National Aeronautics and Space Administration (NASA) Goddard Space Flight Center (POWER/Data Access Viewer 2022). Monthly data of global solar radiation on a horizontal surface were obtained from the archives of 30 years between January 1991 and December 2020 from the NASA website (Data Access Viewer 2022).

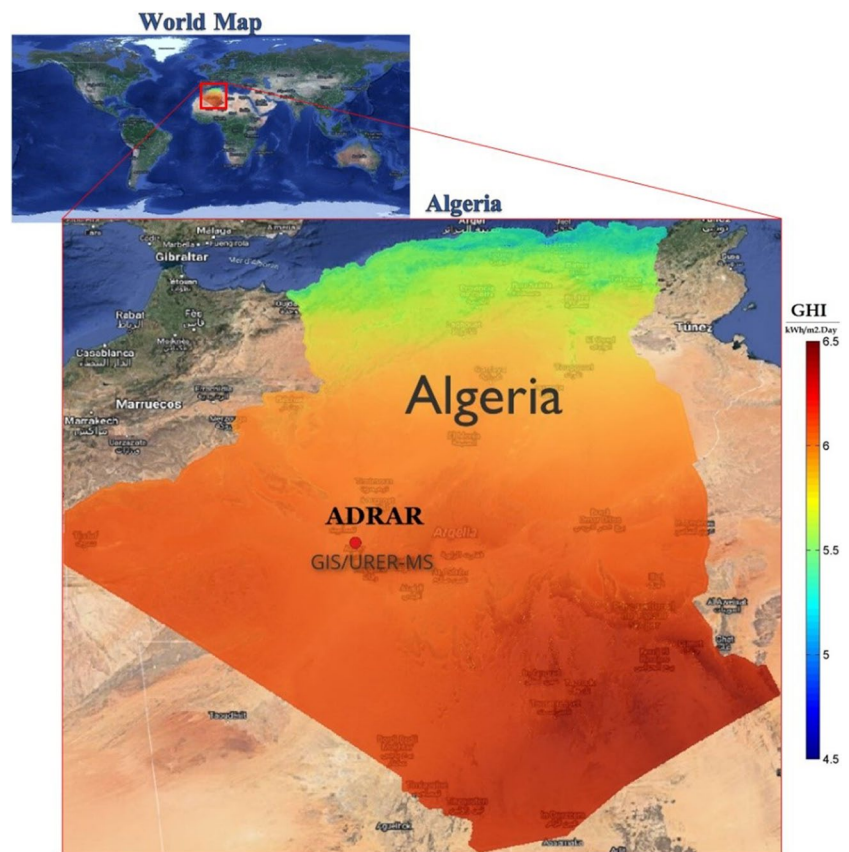
This paper is organized as follows: Sect. 2 presents the data and methods employed in this study. Section 3 is dedicated to the presentation and discussion of the results. Finally, in Sect. 4, we summarize the primary conclusions and discuss possible future work on the subject.

2 Materials and methods

2.1 Study area

This study was carried out in the southwestern region of Algeria (Fig. 1), exactly in the province of Adrar. This

Fig. 1 Geographic location, the annual average of the daily GHI, and the location of GIS/URER/MS station at Adrar



region is rich in solar potential, as can be seen in Fig. 1, which illustrates the spatial distribution of the annual average of daily global solar irradiation at the surface (Bouchouicha et al. 2015; Razagui et al. 2017; Bouchouicha and Oulimar 2013); the final illustration of the image was made by using QGIS Software v3.30.3 (QGIS 2023). With a hot desert climate (Köppen climate classification: BWh) (Hassan et al. 2022; El-kenawy et al. 2021), the region is characterized by very high daily temperatures in summer; moderate in winter, and uniformly low relative humidity. The mean temperature is 27 °C with an average daily maximum of 34 °C and an average daily minimum of 20 °C: July is the hottest month of the year with an average monthly maximum temperature of 46.8 °C, and January is the coldest month with an average monthly minimum temperature of 6.4 °C (Oulimar et al. 2022). The relative humidity is about 24% (Data Access Viewer 2022). Rainfall is very rare throughout the year. The average sunshine duration is about 9.7 h per day (Oulimar et al. 2022) (Oulimar et al. 2022). There are no distinct seasons except for the dust wind period which lasts from around March to May and occasionally in winter when there is bad weather in the north of the region. Meteorological measurements such as sunshine hours and solar radiation are given in solar time, which coincides with Greenwich Mean Time.

2.2 Measurement data

The radiometric measurements play a very important role in any dimensioning and characterization of a solar system, and any measurement uncertainty contributes to the overall doubt of a result, The radiometric uncertainty can be created from three sources: calibration of measurement instrumentation; data acquisition and recording equipment; data saving and processing (Myers 2013).

The long-term measurements used in this study were collected at the meteorological and radiometric station belonging to the Renewable Energy Research Unit in the Saharan Environment (URER/MS) in Adrar. The station is affiliated with the Algiers Renewable Energy Development Center (CDER) and is situated at a latitude of 27.52° N and a longitude of 0.18° W, with an elevation of 292 m above sea level (Bouchouicha and Oulimar 2013). Figure 1 shows the geographical location of the GIS/URER/MS station. Solar irradiance data has been recorded since 1995, but a reliable and accurate dataset, achieved through the deployment of more measurement instruments, starts from January 2010. Current data on solar radiation for horizontal surfaces (global and diffuse radiation scattered by the sky) and inclined south-facing surfaces have been measured using Kipp & Zonen Delft BV CM11 Pyranometers, which are

considered to constitute a secondary standard according to the ISO 9060 norm.

The radiometric station is equipped with CM11 Kipp & Zonen pyranometers for measuring global solar radiation on horizontal surfaces and inclined south-facing surfaces as shown in Fig. 2a and b, respectively. It also includes a sun tracker and an Eppley NIP Pyrheliometer with a solar tracker device for measuring direct solar radiation (Fig. 2c). In addition, there is a pyranometer equipped with a Kipp & Zonen CM11/121 shadowband to measure the diffuse component of solar radiation (Oulimar et al. 2022) (Fig. 2d). Furthermore, it features a Type J thermocouple for temperature measurement (Fig. 2e). Finally, a photovoltaic solar kit is installed to ensure nearly complete energy self-reliance throughout the day.

All instruments have been periodically calibrated following World Meteorological Organization (WMO) recommendations at the Algerian Meteorological Office's calibration laboratory in Tamanrasset, with regional standards referenced as WMO AHF29225 and International Pyrheliometer Comparison (IPC-XI) 2011. All these measurements are taken every second with a Fluke 2635A Hydra Data Acquisition Unit and then averaged and recorded every minute. The station undergoes manual supervision, including visual inspection of leveling, cleaning of the optics, and checking of clocks..., every day. For a schematic of the setup of the station, see Fig. 2.

2.3 NASA/POWER CERES/MERRA2 data

To expand the analysis of time series data in accordance with the standard climatological normal corresponding to a 30-year climatological period according to the latest WMO guidelines (OMM 2017), a second set of data has been employed in this study; the MERRA-2 data set is available at <http://gmao.gsfc.nasa.gov/reanalysis/MERRA-2> and provided by NASA/Goddard Space Flight Center.

Solar POWER data is inferred based on satellite observations; meteorological parameters are based on the MERRA-2

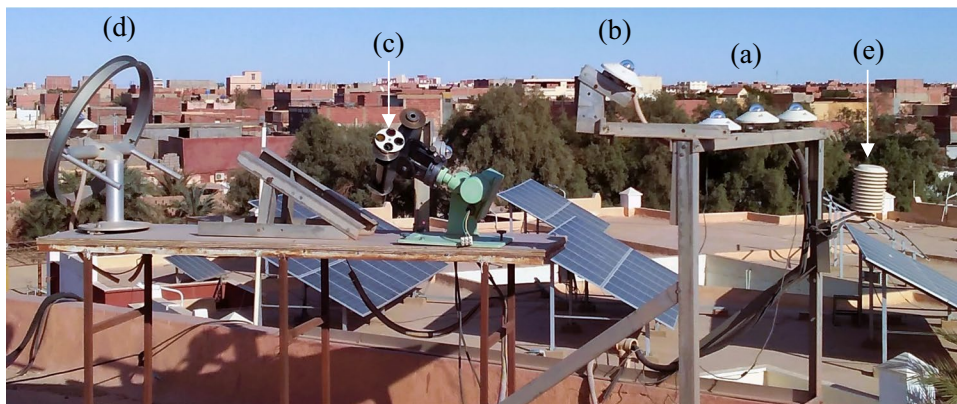
assimilation model. Uncertainty estimates are based on comparisons with surface measurements. A more detailed description of the parameters and the procedures used to estimate their uncertainties is given on the NASA website (NASA Prediction of Worldwide Energy Resources) (POWER/Data Access Viewer 2022). Other validation results have been reported by (White et al. 2011) and (Bouchouicha et al. 2015; 2019; 2018); in this work, monthly data of global solar radiation on a horizontal surface were obtained from the archives of the National Aeronautics and Space Administration (NASA) (POWER/Data Access Viewer 2022) during 30 years between January 1991 and December 2020. The data are used in the extended analysis. MERRA-2 data have demonstrated their performance in reproducing historical climate and their ability to complement observed data through comparisons with surface measurements (Razagui et al. 2021; Jed et al. 2022).

2.4 Methodology

The dataset employed in this study consists of 1-min interval data obtained from the URER-MS station. The global horizontal and diffuse irradiance measurements over this station for 10 years are pre-processed by the EPSE team. The detailed description of how daily and monthly data averages and totals are calculated can be found on the WRDC website (WMO World Radiation Data Centre 2018). The data have been prepared for analysis at various temporal scales, with a particular emphasis on conducting hourly, daily, monthly, seasonal, and annual analyses.

The graphical statistical analysis of long-term solar irradiance data is performed using appropriate visualizations, such as time series plots, box plots, and histograms. A variety of graphical tools and approaches were used for visually exploring, analyzing, and interpreting the dataset at various time scales (hourly, daily, monthly, seasonal, and annual) in order to gain insights and identify trends and patterns in the data. Additionally, statistical properties such as minimum, maximum, mean, and standard deviation of the time series

Fig. 2 The measurement station (GIS/URER/MS)



are examined to detect potential temporal changes. In order to analyze the interannual variability of the global solar radiation, we employ the standardized variable index (denoted as “I”), as defined by the following equation (Célestin et al. 2019):

$$I(i) = \frac{X_i - \bar{X}_i}{\sigma} \tag{1}$$

where X_i , \bar{X}_i , and σ are respectively the value for the considered year (or month i), the average, and the standard deviation of the time series. We considered that a year is normal when its index is included between -1.0 and $+1.0$. It will be in surplus if its index is greater than $+1$, and will be considered a deficit when its index is below -1 .

3 Results and discussion

The evaluation of long-term solar irradiance measurement variability was carried out across various time scales, including hourly, daily, monthly, and interannual, spanning the period from 2011 to 2020. In order to assess the variations in solar irradiance throughout the year and across different times of the day, we calculated the average solar irradiance values for specific hours (averaged over days and months) and for individual months (averaged over hours and days). The graphical statistics analysis, using various graphical tools (time series plot, monthly and seasonal averages, box plots, histograms, etc.) are presented in the following paragraphs.

3.1 Hourly irradiation

The hourly change of the global solar radiation on the horizontal plane (Fig. 3) shows that the hourly change per day of radiation on a horizontal plane varies during the day from

sunrise to sunset, it exceeds 500 Wh/m^2 between 9 a.m. and 3 p.m. the maximum is recorded around solar noon with over 800 Wh/m^2 .

For the hourly change per month in the year (Fig. 4), when we take the average of the hourly energy for the peak hour at solar noon over all the years studied, we notice that the month of June records an average of about 1000 Wh/m^2 at this time, for the other month the average of the hourly energy at noon is above 600 Wh/m^2 at this time.

A heatmap illustrating the intensity of hourly global solar irradiance across the months is presented in Fig. 5. The horizontal columns represent the hours of the day, while the vertical rows represent the months of the year.

The hours with the highest values are evident by the presence of warmer red colors. The figure illustrates that the site experiences consistently high solar radiation intensity throughout the year. On a monthly basis, the intensity reaches its peak between 11:00 a.m. and 2:00 p.m. local time. In June, the hourly peak of solar irradiance reaches 1007.2 Wh/m^2 .

To analyze the distribution of hourly solar irradiation over the entire time series, we utilize a frequency distribution graph presented in Fig. 6; we select specific data within the time range of 09:00 to 16:00 local time (GMT + 1). This corresponds to a time range that excludes sunrise and sunset time throughout the year and to avoid the measurement affected by natural masks, especially at the beginning and end of the day.

From the frequency histogram shown in Fig. 6, it was observed that the highest peak frequencies correspond to the range of global solar radiation between 600 and 700 Wh/m^2 with a value equal to 15.08% . On the other hand, the lowest peak frequencies in the histogram correspond to the range of solar radiation below 100 W/m^2 with a value equal to 3.39% . We can observe that all other ranges of solar radiation, especially the ranges within 300 to 1000 Wh/m^2 have near values

Fig. 3 Hourly global irradiation distribution measurements at Adrar station (2011–2020)

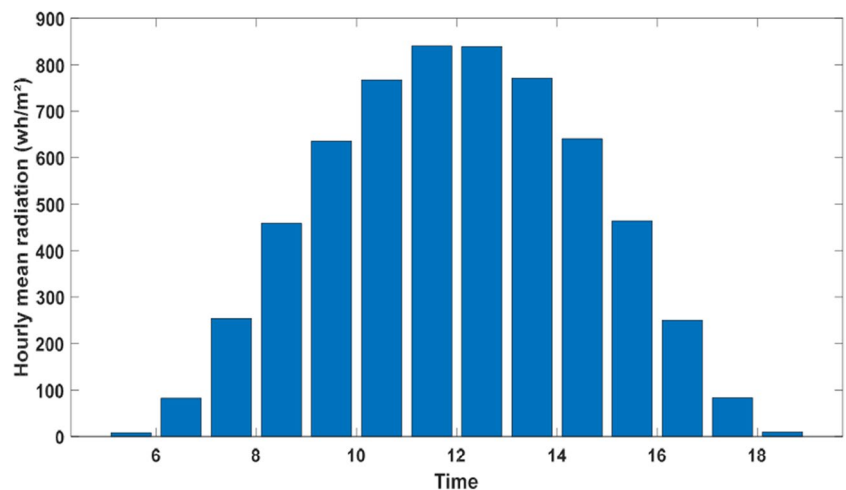


Fig. 4 Monthly average hourly global irradiation distribution on a horizontal plane—Adrar (2011–2020)



Fig. 5 Monthly average hourly global irradiation distribution on a horizontal plane—Adrar (2011–2020)

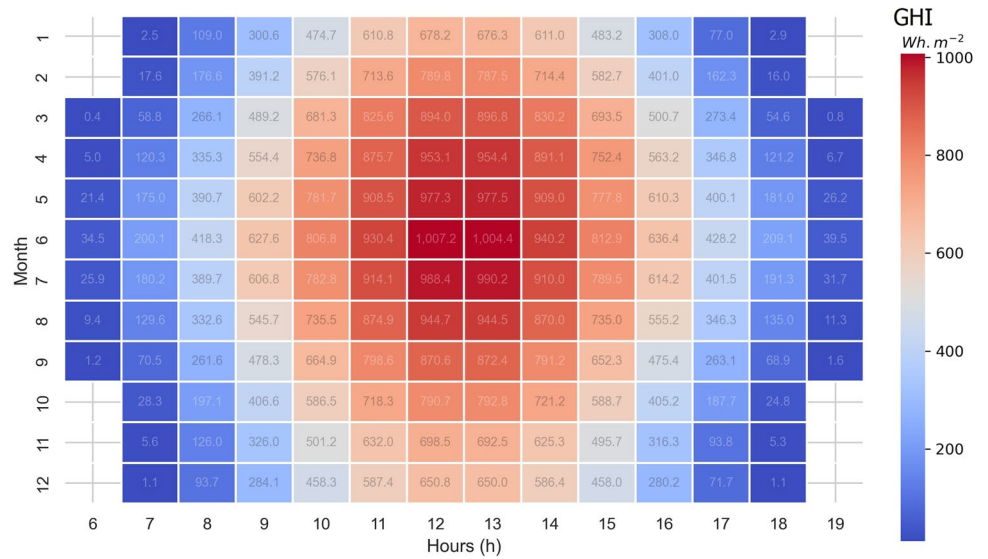
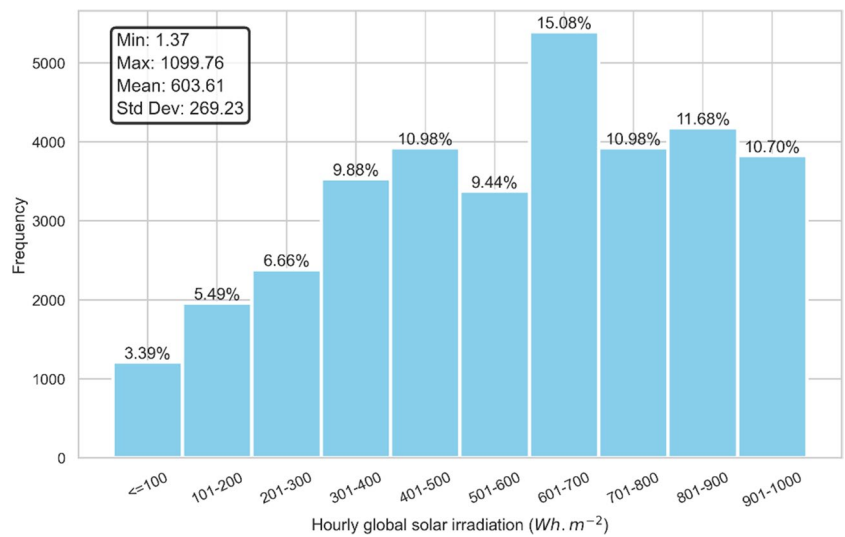


Fig. 6 Frequency distribution of hourly solar irradiation



of frequency distribution, and the hourly solar irradiance of more than 300 Wh/m² occurs about 84.5%.

3.2 Daily irradiation

The daily change of the global solar radiation on the horizontal plane (Fig. 7) shows that it changes per day of radiation during the year from January to December. The daily energy is calculated from sunrise to sunset for each day of the year; it exceeds 3.5 kWh/m² for most days of the year. The maximum is recorded between June 5th and 15th with more than 8.4 kWh/m² per day; in this decade (2011–2020), the average of the day which recorded the maximum energy is June 10 with over 8.5 kWh/m².

Understanding how daily global irradiation varies by month or season is crucial for solar energy applications, especially in system design and maintenance. In this context,

the monthly average and total of daily global solar radiation on horizontal surfaces using the daily data are calculated for each month over a period of 10 years from 2011 to 2020. Figure 8 represents the monthly distribution of daily global horizontal irradiation.

In Fig. 9, we can find a representation of the monthly average and total of daily global solar radiation on horizontal surfaces. It can be observed that the monthly mean and total variations of radiation during the year from January to December, the monthly mean energy is calculated from all days of each month in this studied decade (2011–2020); it has a minimum in December with over 4000 Wh/m²/day and a maximum of 8000 Wh/m²/day in June. The monthly total radiation is calculated by summing of energy of all days of the month in the year; it has also a minimum in December of 126 kWh/m²/month and a maximum of 242 kWh/m²/month in July.

Fig. 7 Daily global irradiation on a horizontal surface at Adrar (2011–2020). The red line shows the 10 years daily average

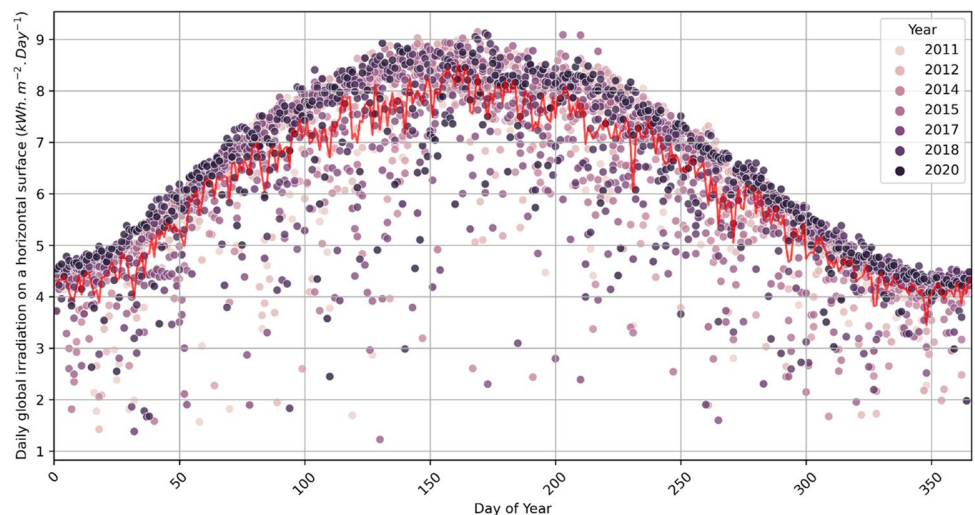
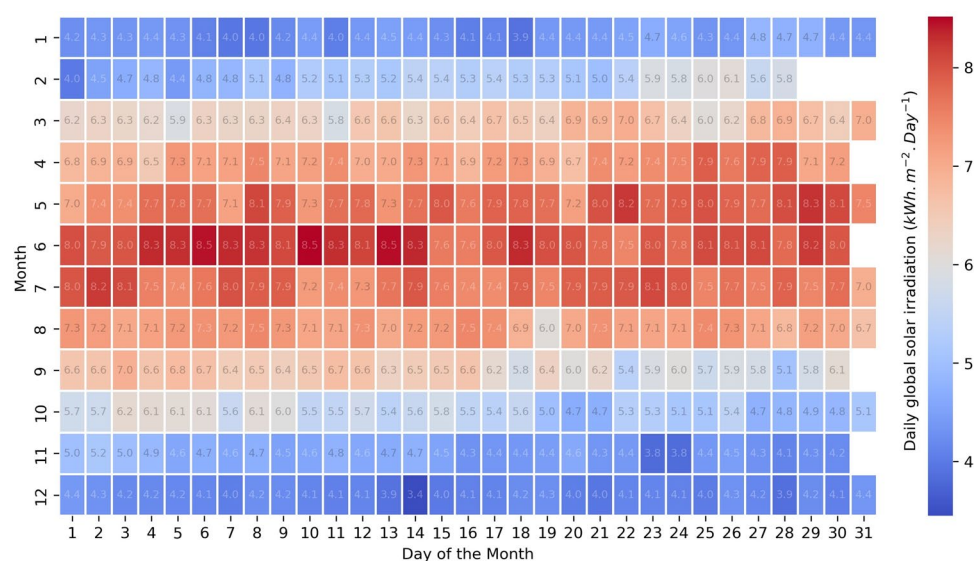


Fig. 8 Monthly average of daily global horizontal irradiation distribution—Adrar (2011–2020)



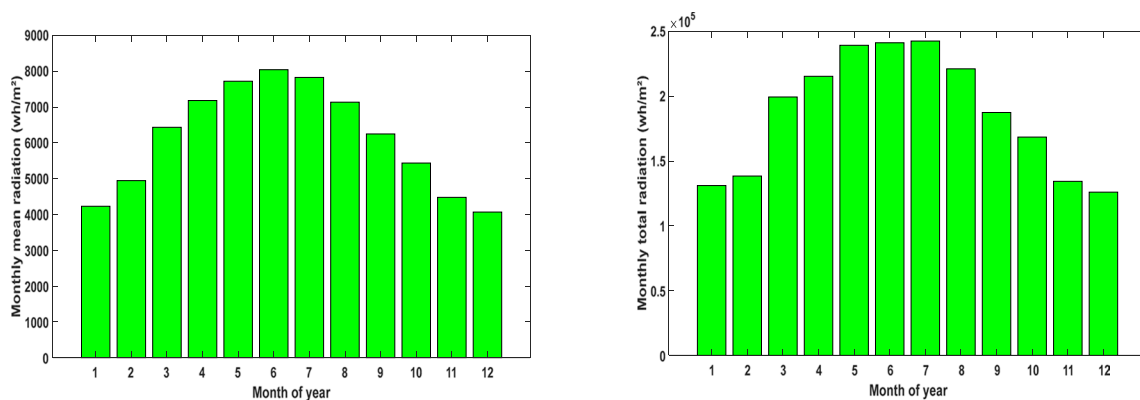


Fig. 9 Monthly average daily and total global irradiation—Adrar site (2011–2020)

The box plots of seasonal and annual variability of global solar irradiation at the surface are presented in Fig. 10a and b, respectively. The line within each box corresponds to the median values, while the boxes and vertical bars visually represent the extent of annual average variation, taking into account one-standard deviation and two-standard deviation intervals.

Figure 10a shows that during the summer months, the median of the global solar irradiation is higher with less variability compared to the other seasons, while the winter season exhibits the lowest intensity. The amplitude of the daily variability of solar radiation is wider in spring and autumn. This observed behavior aligns with the prevailing climatic conditions experienced during these specific seasons, which can be attributed to the influence of cloud cover and the presence of dust particles in the atmosphere.

The box plots in Fig. 10b highlight the diverse annual variations in daily global solar irradiation over the decade from 2011 to 2020. The datasets exhibit significant differences in median and standard deviation over the years, with noticeable positive and negative trends. The annual average value is about 6.18 kWh/m²/day, the maximum, of about

6.34 kWh/m²/day, is reached in 2019, and the minimum, of around 5.98 kWh/m²/Day, is reached in 2017. In terms of annual total energy, the value ranges from 2.1 to 2.3 MWh/m² per year.

Daily global solar irradiation frequency histogram was conducted using 10 years of data (Fig. 11). The figure shows that daily solar irradiance of more than 4 kWh/m²/day occurs about 92.1%. The highest frequency occurs at solar irradiance of 4–5 kWh/m²/day, with a value equal to 22.66%.

Another important aspect to consider regarding daily solar irradiation is identifying interannual variability using the standardized variable index. As shown in Fig. 12, a statistically significant positive trend was observed on an annual basis during two periods: from 2011 to 2013 and from 2017 to 2019, with significance in the latter period. In contrast, a negative trend was observed from 2013 to 2017.

3.3 Climatological normal

In this part, we use data from the latest standard climatological normal, which now refers to the most recent 30-year period whose last year ends with the number 0

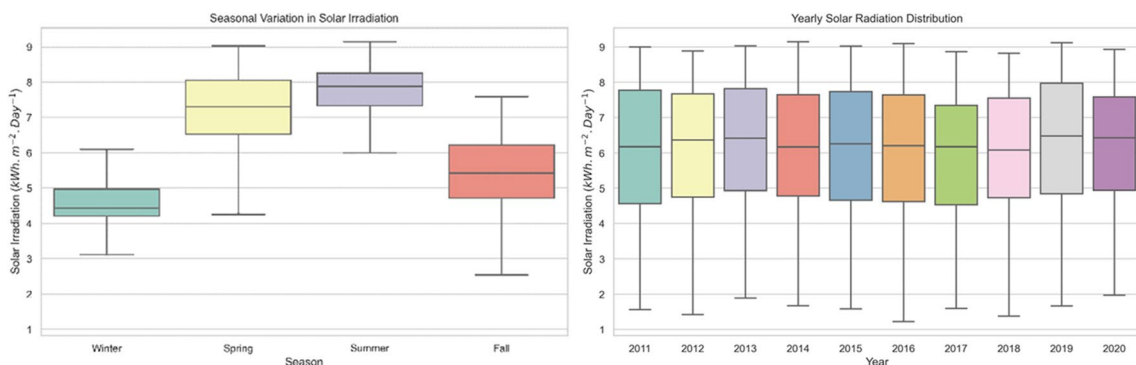


Fig. 10 Box plots of seasonal and annual variability of daily global solar irradiation

Fig. 11 Frequency histogram of daily global solar irradiation

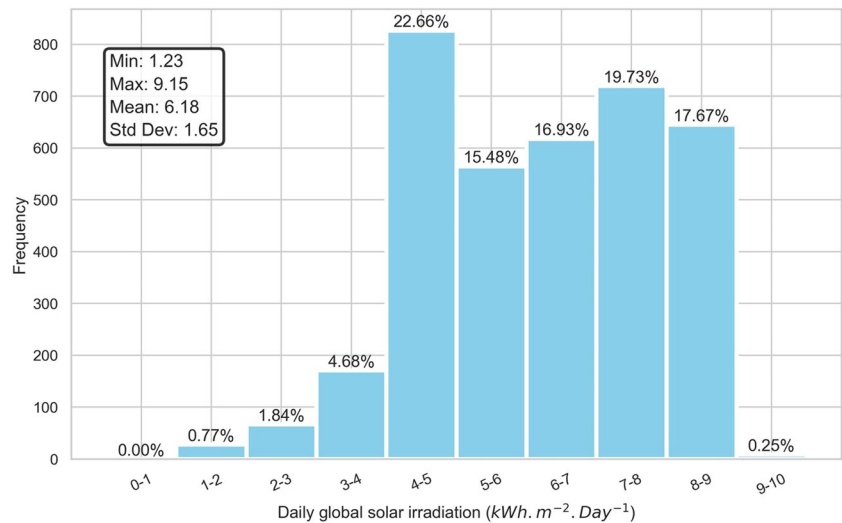
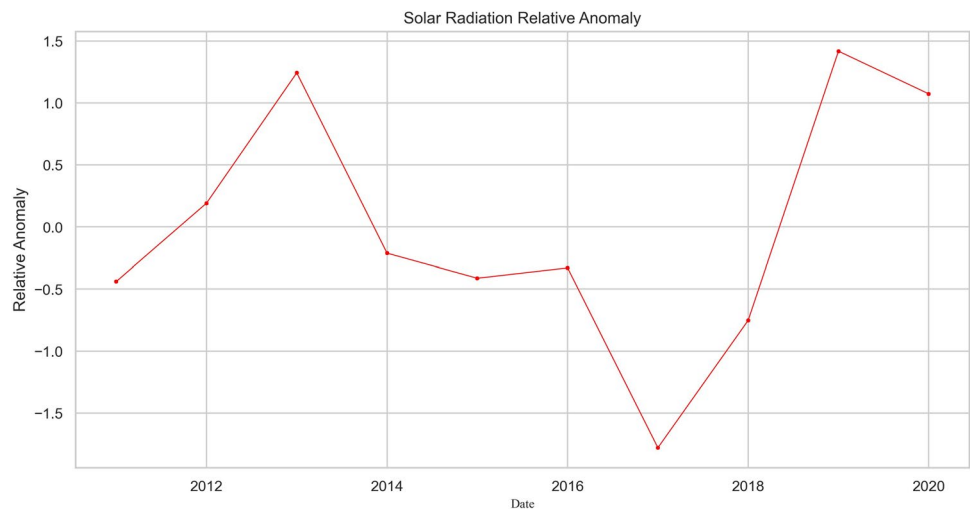


Fig. 12 Standardized variable index of the annual time series



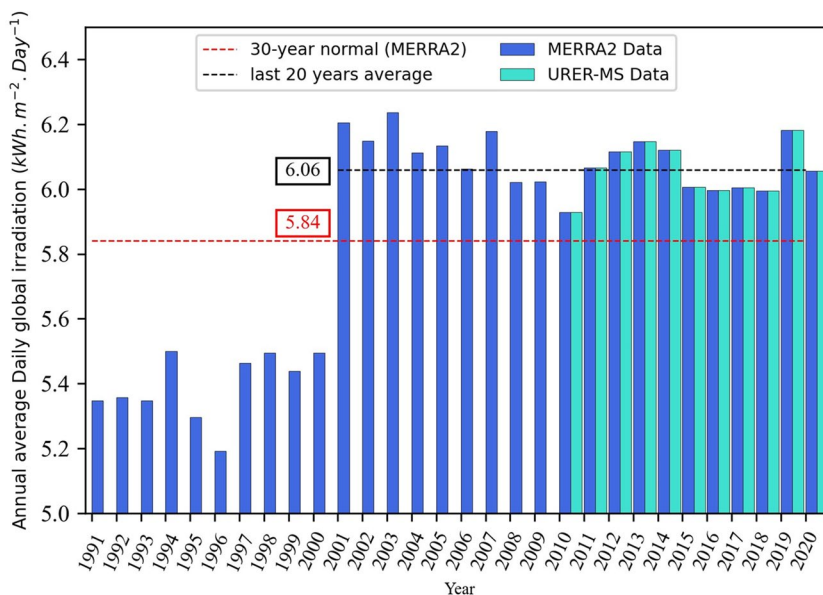
(1991–2020) according to the latest WMO guidelines (OMM 2017), and because of the insufficiency of our database (URER/MS database), we referred to the annual data of MERRA2 (Data Access Viewer 2022) for the period (1991–2020), but we noticed an abrupt change in the rhythm of the data in 2001. This may be due to the data sorting method and the sources of this database. According to our investigation on the “POWER” site (NASA POWER/Docs 2022), we found that the parameters of energy flow (for example, solar irradiance) are derived from NASA’s GEWEX SRB Release 4-Integrated Product (R4-IP) archives (January 01, 1984, to December 31, 2000) (Zhang et al. 2017; Pinker and Laszlo 1992) and NASA’s CERES SYN1deg and FLASHFlux projects (January 1, 2001, to NRT minus ~3–4 months). This examination is confirmed by the corresponding NASA Power team which says that in 2001, the data source changes from GEWEX SRB to CERES SYN1deg. Because of this,

there is a mismatch of data, and they will introduce a bias-corrected flux for the future data version.

The statistics of the annual change of global solar radiation on the horizontal plane (Fig. 13) in the latest period of the standard climatological normal (1991–2020) shows that the normal in this period is 5.84 kWh/m², but if we eliminate the first period of the sudden change in the data (1991–2000), and we calculate the average over 20 years (2001–2020), we find an average of 6.06 kWh/m²/year.

When we compare our annual data to that of MERRA2, we notice a similarity and almost an equality between these two data sources, which makes the analysis of this climatological series of the last 20 years very useful for climatological studies of solar radiation, and we found that the annual average solar radiation on a horizontal plane for our data does not deviate much from the average of the last 20 years (difference of 0.07 kWh/m²) and that the variation of the radiation in these last decades shows a surplus compared

Fig. 13 Comparison of annual data of global irradiation measured in Adrar (2011–2020) and estimated by MERRA2 in the last period of the standard climatological normal (1991–2020)



to the average for the years (2012–2014), then a decrease compared to the average for the years (2015–2018), and then a sudden increase in 2019 (0.18 kWh/m^2) compared to the previous 4 years.

4 Conclusion

This work investigated the global horizontal solar irradiation variability in the southern Algerian region, based on a graphical statistical analysis of ground data collected at the meteorological and radiometric station belonging to the Renewable Energy Research Unit in the Saharan Environment (URER/MS) in Adrar during the decade 2010–2020. The data have been prepared for analysis at various temporal scales, with a particular emphasis on conducting hourly, daily, monthly, seasonal, and annual analyses.

Hourly and daily global horizontal solar irradiation were analyzed. The statistics of the hourly data show variation during the day from sunrise to sunset; it exceeds 500 Wh/m^2 between 9 a.m. and 3 p.m. The maximum is recorded around solar noon with more than 800 Wh/m^2 . For the monthly variation of the hourly energy, we took the average of the hourly energy for the peak hour at solar noon over all the years studied; we noticed that the month of June records an average of about 1000 Wh/m^2 during this period. For the other months, the average hourly energy at noon is greater than 600 Wh/m^2 . The daily variation of global solar irradiation shows that the daily energy exceeds 3.5 kWh/m^2 for most days of the year. The maximum is recorded from June 5 to June 15 with more than 8.4 kWh/m^2 per day; in this decade (2011–2020), the average of the day recorded the maximum energy is June

10 with more than 8.5 kWh/m^2 . The monthly variation of global solar radiation shows significant variation in average and total radiation during the year from January to December. The minimum was recorded in December with more than $4 \text{ kWh/m}^2/\text{day}$ and a maximum of $8 \text{ kWh/m}^2/\text{day}$ in June. The monthly total radiation also has a minimum in December of $126 \text{ kWh/m}^2/\text{month}$ and a maximum of $242 \text{ kWh/m}^2/\text{month}$ in July. For the annual energy variation, the average global radiation on a horizontal plane varies during this last decade by about $6 \text{ kWh/m}^2/\text{year}$, the total energy of all the years of this period (2011–2020) is uniformly stable, and it varies around $2.2 \text{ MWh/m}^2/\text{year}$.

The interannual variability analysis was made using a standardized variables index. The results showed significant positive and negative trends were respectively detected through the time series over the last decade, with a high-significant positive trend observed during 2017 and 2019.

The comparison between our measurements made at the URER/MS and that estimated by MERRA2 in the last standard climatological normal (1991–2020) shows that the global radiation on a horizontal plane has an important similarity and is almost equal to the annual data. We found that the average annual solar radiation for our data (6.16 kWh/m^2) does not deviate much from the average of the last 20 years (6.09 kWh/m^2). In summary, this study made it possible to give a general view of the temporal variation of solar radiation with data measured on the ground and over a relatively sufficient period for all studies and programming of a solar installation. The extension of the analysis over a period of 30 years by data from the MERRA2 project has made it possible to conclude that the order of magnitude of our data is acceptable for the last 20 years and that the data from the NASA project are acceptable for our region and

can be used for other sites where there is no radiometric measurement.

Finally, the results could provide reliable and useful information for the effective planning, design, implementation, and management of renewable energy projects, especially those that rely on solar energy. They optimize performance, maximize profitability, and contribute to the transition to cleaner and more sustainable energy sources.

In future research, other components (diffuse and beam) of solar radiation can be studied, additional parameters and statistical methods will be applied, and supplementary Algerian regions will be taken into account according to the availability of data.

Author contribution Ibrahim Oulimar and Kada Bouchouicha wrote the main text of the manuscript and prepared and processed the data.

Nadjem Bailek and Mabrouk Bellaoui gave directions on the data analysis and interpretation and aided in reviewing and editing the manuscript.

All authors discussed the results and read and accepted the final manuscript.

Declarations

Consent to participate All authors consent to participate in the study.

Consent for publication All authors consent to publish the study in a journal article.

Competing interests The authors have no conflicts of interest to declare that are relevant to the content of this article.

References

- Bellaoui M, Bouchouicha K (2020) Oulimar I 2021 “Estimation of daily global solar radiation based on MODIS satellite measurements: the case study of Adrar region (Algeria).” *Meas: J Intl Meas Confederation* 183:109802. <https://doi.org/10.1016/j.measurement.2021.109802>
- Bouchouicha K (2017) *Modelisation Multispectrale Des Images Satellitaire-Application : Quantification Du Bilan d'energie Sol-Atmosphere*. Thesis, USTO
- Bouchouicha K, Razagui A, Bachari NI, Aoun N (2015) Mapping and geospatial analysis of solar resource in Algeria. *Int J Energy, Environ Econ* 23(6):735–751
- Bouchouicha K, Bailek N, Mahmoud ME, Alonso JA, Slimani A, Djaafari A (2018) Estimation of monthly average daily global solar radiation using meteorological-based models in Adrar, Algeria. *Appl Solar Energy* 54(6):448–455. <https://doi.org/10.3103/S0003701X1806004X>
- Bouchouicha K, Hassan MA, Bailek N, Aoun N (2019) Estimating the global solar irradiation and optimizing the error estimates under Algerian desert climate. *Renew Energy* 139(August):844–858. <https://doi.org/10.1016/j.renene.2019.02.071>
- Bouchouicha K, Bailek N, Bellaoui M, Oulimar B, Benatallah D (2021) ANN-based correction model of radiation and temperature for solar energy application in south of Algeria. *Lect Notes Networks Syst* 174. https://doi.org/10.1007/978-3-030-63846-7_55
- Bouchouicha K, Bailek N, Razagui A, EL-Shimy M, Bellaoui M, Bachari NE (2021) Comparison of artificial intelligence and empirical models for energy production estimation of 20 MWp solar photovoltaic plant at the Saharan Medium of Algeria. *Int J Energy Sect Manag* 15(1):110–138. <https://doi.org/10.1108/IJESM-12-2019-0017>
- Bouchouicha K, Oulimar B (2013) La chaine de mesure radiométrique à l'Unité de Recherche en Energie Renouvelable en Milieu Saharien d'Adrar. In: *International Conference on Energy and Sustainable Development* (Vol. 13)
- Célestin M, Emmanuel LA, Batablinè L, Marc N (2019) Spatio-temporal analysis of climate change impact on future wind power potential in Burundi (East Africa). *Am J Clim Chang* 08(02):237–262. <https://doi.org/10.4236/ajcc.2019.82014>
- CEREFÉ (2020) *Transition Energétique en Algérie : Leçons, Etat des Lieux et Perspectives pour un Développement Accéléré des Energies Renouvelables*, (Edition 2020) : Commissariat aux Energies Renouvelables et à l'Efficacité Energétique, Premier Ministre, Alger. www.cerefe.gov.dz
- Data Access Viewer (2022) Prediction of worldwide energy resource (POWER). <https://power.larc.nasa.gov/data-access-viewer/>. Accessed 8 Sept 2022
- Dokkar A, Settou N, Dokkar B, Messoudi D (2023) Analysing the impact of increasing renewable energy shares on Algerian energy system for prospective transition scenarios. *Tobacco Regul Sci* 9(1):4595–4614. <https://doi.org/10.18001/TRS.9.1.321>
- El-kenawy ES, Ibrahim A, Bailek N, Bouchouicha K, Hassan MA, Jamei M, Al-Ansari N (2021) Sunshine duration measurements and predictions in Saharan Algeria region: an improved ensemble learning approach. *Theor Appl Climatol* 147(3):1015–1031. <https://doi.org/10.1007/S00704-021-03843-2>
- El-Kenawy ES, Ibrahim A, Bailek N, Bouchouicha K, Hassan MA, Jamil B, Al-Ansari N 2022. “Hybrid ensemble-learning approach for renewable energy resources evaluation in Algeria.” *Comput Mater Contin* 71(2). <https://doi.org/10.32604/cmc.2022.023257>.
- Feng Z, Guo B, Han Xu, Zhang L, Jie Xu, Ying Xu (2021) A new view on the trend of solar radiation in Mainland China — based on the optimized empirical model. *Theor Appl Climatol* 145(1–2):519–532. <https://doi.org/10.1007/s00704-021-03643-8>
- Friedlingstein P, O'sullivan M, Jones MW, Andrew RM, Gregor L, Hauck J, Le Quéré C et al (2022) *Global Carbon Budget 2022*. *Earth Syst Sci Data* 14(11):4811–4900. <https://doi.org/10.5194/ESSD-14-4811-2022>
- Goliatt L, Yaseen ZM 2023. “Development of a hybrid computational intelligent model for daily global solar radiation prediction.” *Expert Syst Appl* 212. <https://doi.org/10.1016/j.eswa.2022.118295>.
- Guermoui M, Bouchouicha K, Bailek N, Boland JW 2021. “Forecasting intra-hour variance of photovoltaic power using a new integrated model”. *Energy Convers Manag* 245. <https://doi.org/10.1016/j.enconman.2021.114569>.
- Hassan MA, Bailek N, Bouchouicha K, Ibrahim A, Jamil B, Kuriqi A, Nwokolo SC, El-kenawy ES (2022) Evaluation of energy extraction of PV systems affected by environmental factors under real outdoor conditions. *Theor Appl Climatol* 150(1–2):715–729. <https://doi.org/10.1007/s00704-022-04166-6>
- Hassan MA, Bailek N, Bouchouicha K, Nwokolo SC 2021. “Ultra-short-term exogenous forecasting of photovoltaic power production using genetically optimized non-linear auto-regressive recurrent neural networks”. *Renew Energy* 171. <https://doi.org/10.1016/j.renene.2021.02.103>.
- IRENA (2023) *Renewable energy statistics 2023*, International Renewable Energy Agency, Abu Dhabi
- Jed M, Ihaddadene N, Jed ME, Ihaddadene R, El Bah M (2022) Validation of the accuracy of NASA solar irradiation data for four

- African regions. *Int J Sustain Dev Plan* 17(1):29–39. <https://doi.org/10.18280/ijdp.170103>
- Katipoğlu OM (2022) Analyzing the trend and change point in various meteorological variables in Bursa with various statistical and graphical methods. *Theoret Appl Climatol* 150(3–4):1295–1320. <https://doi.org/10.1007/s00704-022-04231-0>
- Keshtegar B, Bouchouicha K, Bailek N, Hassan MA, Kolahchi R, Despotovic M (2022) “Solar irradiance short-term prediction under meteorological uncertainties: survey hybrid artificial intelligent basis music-inspired optimization models”. *Eur Physical J Plus* 137(3). <https://doi.org/10.1140/epjp/s13360-022-02371-w>
- Makade RG, Chakrabarti S, Jamil B (2021) “Development of global solar radiation models: a comprehensive review and statistical analysis for Indian regions”. *J Clean Prod Elsevier Ltd*. <https://doi.org/10.1016/j.jclepro.2021.126208>
- Manara V, Bassi M, Brunetti M et al (2019) 1990–2016 surface solar radiation variability and trend over the Piedmont region (north-west Italy). *Theor Appl Climatol* 136:849–862. <https://doi.org/10.1007/s00704-018-2521-6>
- Myers DR (2013) “Introduction to solar radiation measurements.” In *Solar Radiation*, 15–42. CRC Press. <https://doi.org/10.1201/b13898-2>
- NASA POWER/Docs (2022). <https://Power.Larc.Nasa.Gov/Docs/Methodology/Data/Sources/>. Accessed 21 Sept 2022
- Nunez M, Li Y (2008) A cloud-based reconstruction of surface solar radiation trends for Australia. *Theoret Appl Climatol* 91(1–4):59–75. <https://doi.org/10.1007/s00704-006-0287-8>
- Okono MA, Agbo EP, Ekah BJ, Ekah UJ, Ettah EB, Edet CO (2022) Statistical analysis and distribution of global solar radiation and temperature over Southern Nigeria. *J Nigerian Soc Phys Sci* 4(3):588. <https://doi.org/10.46481/jnsps.2022.588>
- OMM (2011) Guide des pratiques climatologiques (OMM-N° 100), Édit. Organisation Météorologique Mondiale, Genève, Suisse, (100):152. http://www.hydrosciences.fr/sierem/Bibliotheque/biblio/wmo_100_fr.pdf
- OMM (2017) Directives de l’OMM pour le calcul des normales climatiques, p 20. https://library.wmo.int/doc_num.php?explnum_id=4220
- Oulimar I, Benatiallah A, Bouchouicha K (2020) “Validation modeles and simulation of global horizontal solar flux as a function of sunshine duality in Southern Algeria (Adrar).” In *Lecture Notes in Networks and Systems*. 102. https://doi.org/10.1007/978-3-030-37207-1_21
- Oulimar I, Bouchouicha K, Hadji Y, Bellaoui M (2022) EPESE Team; URER/MS, CDER, Adrar. Adrar. <https://urerm.s.cder.dz/-4فرفرة/>
- Pinker RT, Laszlo I (1992) Modeling surface solar irradiance for satellite applications on a global scale. *J Appl Meteorol* 31(2):194–211. [https://doi.org/10.1175/1520-0450\(1992\)031%3c0194:MSSIFS%3e2.0.CO;2](https://doi.org/10.1175/1520-0450(1992)031%3c0194:MSSIFS%3e2.0.CO;2)
- POWER/Data Access Viewer (2022) Prediction of worldwide energy resource. <https://power.larc.nasa.gov/data-access-viewer/>. Accessed 28 June 2022
- QGIS (2023) QGIS Official Website. <https://www.qgis.org/en/site/>
- Razagui A, Bachari NII, Bouchouicha K, Hadj Arab A (2017) Modeling the global solar radiation under cloudy sky using Meteosat second generation high resolution visible raw data. *J Indian Soc Remote Sens* 45(4):725–732. <https://doi.org/10.1007/s12524-016-0628-8>
- Razagui A, Abdeladim K, Bouchouicha K, Bachari N, Semaoui S, Hadj Arab A (2021) A new approach to forecast solar irradiances using WRF and LibRadtran models, validated with MERRA-2 reanalysis data and pyranometer measures. *Sol Energy* 221(June):148–161. <https://doi.org/10.1016/j.solener.2021.04.024>
- Salhi H, Hadjira A, Jamil B (2023) Statistical analysis of the solar diffuse fraction radiation using regression analysis of longitudinal data in India. *J Ther Eng* 9(3):776–85. <https://doi.org/10.18186/thermal.1300542>
- Torbus SA, Mroczńska K, Kreft-Korda J, Grabarczyk S (2023) Extended statistical analysis of the results of solar radiation intensity measurements. *Rynek Energii* 2023(1):35–39
- Upadhyay Y, Jamil B, Saud S (2023) Implementing an advanced data-driven response surface approach to estimate global solar radiation based on multiple inputs. *Theor Appl Climatol* 152(3):1075–1094. <https://doi.org/10.1007/s00704-023-04448-7>
- Watanabe T, Oishi Y, Nakajima TY (2016) “Characterization of surface solar-irradiance variability using cloud properties based on satellite observations”. *Solar Energy* 140. <https://doi.org/10.1016/j.solener.2016.10.049>
- White JW, Hoogenboom G, Wilkens PW, Stackhouse PW Jr, Hoel JM (2011) Evaluation of satellite-based, modeled-derived daily solar radiation data for the Continental United States. *Agron J* 103(4):1242–1251. <https://doi.org/10.2134/agronj2011.0038>
- WRDC (2018) Solar radiation and radiation balance data (the World Network). http://wrdc.mgo.rssi.ru/wwwrootnew/publ/WRDC_issue_2018_4.pdf
- Zagouras A, Kazantzidis A, Nikitidou E, Argiriou AA (2013) “Determination of measuring sites for solar irradiance, based on cluster analysis of satellite-derived cloud estimations.” *Solar Energy* 97. <https://doi.org/10.1016/j.solener.2013.08.005>
- Zhang T, Stackhouse PW, Gupta SK, Cox SJ, Mikovitz JC (2017). “Validating the new results from the next generation of the NASA GEWEX SRB against the BSRN, GEBA, WRDC as well as the PMEL data.” In *AIP Conference Proceedings*. 1810. <https://doi.org/10.1063/1.4975555>

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