

Research Article

Assessment of Long-term Solar Radiation for Energy Exploitation in East-Jerusalem, Palestine

Husain Alsamamra^{*} , Hazem Doufesh , Musa Abutier 

Department of Physics, Al-Quds University, Jerusalem, Palestine

Abstract

Assessment of solar radiation is helpful for engineers concerning the solar energy systems and energy efficiency who can therefore take knowledge of solar radiation levels at a site. This work aims to characterize global solar radiation, meteorological variables and derived solar parameters measured in Jerusalem-Palestine, covering the period 2014-2023. Hourly global solar radiation was investigated into monthly, seasonal, and annually variations of clearness index (K_t). The frequency distribution of hourly K_t show a minimum value of 0.21 to a maximum value 0.8 throughout the entire study period. 75% and 33% of hourly ($0.65 < K_t < 0.75$) values are in summer and winter months, respectively, indicating partially cloudy to more clear sky conditions in Jerusalem. Moreover, K_t is a strong indicator of solar radiation at the study site. During June, daily global radiation value is 28.68 MJ/m^2 , while December value found to be 8.56 MJ/m^2 . The total number of sunshine duration hours ranged between 2755 and 3153, with the lowest recorded in December. Based on the results obtained, Jerusalem is appropriate to harvest solar energy. Further studies could be done to compare ground measurements with satellite observations to improve the spatial distribution of solar radiation in Palestine, particularly in regions where no measurements exist.

Keywords

Solar Radiation, Sunshine Duration, Clearness Index, Solar Energy

1. Introduction

Solar energy stands out as one of the tops fast growing technologies of energy in the world. This is evident from the large amount of applications of solar power that have increased over several decades [1]. In order to evaluate the potential of solar energy in a region, regional solar radiation needs to be determined. One way to do this is to gather long-term measurements of solar radiation data. Understanding the amount of solar radiation is important for evaluating the potential of solar energy applications like thermal engineering, agriculture, and electricity generation [2]. The design, cost analysis, and efficiency calculations of solar

energy conversion systems require such data. Therefore, global solar radiation is one of the main factors that should be explored before and after solar power projects [3-5]. Furthermore, accurate assessment, and interpretation of long-term solar radiation data can significantly impact our ability to harness clean energy from the sun [6]. To determine how effective a solar-powered system is, daily, monthly, and annual solar radiation levels must be analyzed [7, 8]. According to the Palestinian central bureau of statistics, the annual electricity consumption per capita in Palestine is 1279 KWh/Capita in 2022, and around 41% of the total energy

^{*}Corresponding author: hsamamra@staff.alquds.edu (Husain Alsamamra)

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consumption is consumed by the household sector.

Numerous studies have been carried out by the scientific community and addressed this topic because of its sustainability as well as its large application area in electricity generation and agriculture [9, 10]. Hence, the research efforts were focused on the development and advancement to define and estimate the solar radiation potential in a specific site [11, 12], sometimes through the use of empirical models [13, 14] and more recently through artificial intelligence [15, 16].

In Palestine, long-term solar resources assessment and investigation has been received only a little attention with few studies on short term solar energy modeling and estimation reported in the literature [17-19]. There is a clear need for more research studies for developing the solar energy sector, aiding in energy planning, and helping to meet the Palestinian energy needs and reduce electricity costs.

To the best of the author's knowledge, the presented study is the first work in East Jerusalem to examine long-term global solar radiation. The significance of this work comes due to the lack of sufficient of conventional energy sources in the Palestinian territories. In order to promote investment in renewable energy sectors, such as solar energy, the findings of this study could encourage the Palestinian government to make more efforts to establish more legislations and give incentives for investment in renewable energy.

For this reason, in order to assess the solar energy potential in east Jerusalem, Palestine, this work investigates long-term measurements of global solar radiation, meteorological variables and derived solar parameters. A detailed analysis is carried out on the description of sky conditions at the location according to the calculated K_t values. The use of hourly time-series data from 2014 to 2023, is novelty lies behind this study. For individuals that invest in solar energy in the region, this analysis offers insightful feedback and clarifies the solar radiation profile in Jerusalem.

2. Materials and Methods

West Bank, Palestine, its elevation ranges between -276 and 1000 meters above sea level on the eastern Mediterranean coast.

$$H_0 = \frac{24 \times 3600 G_{sc}}{\pi} \left[1 + 0.033 \cos \left(\frac{360n}{365} \right) \right] \times \left[\cos(\phi) \cos(\delta) \sin(w_s) + \left(\frac{\pi w_s}{180} \right) \sin(\phi) \sin(\delta) \right] \quad (1)$$

Where G_{sc} is the solar constant (1370 W/m^2), ϕ is the latitude of the location, the declination angle is δ , n the day number of the year ($n=1$ for January 1 and $n=365$ for December 31) and w_s is derived from the following equation and represents the sunset hour angle in degrees.

$$\cos w_s = -\tan \phi \tan \delta \quad (2)$$

$$\left[1 + 0.033 \cos \left(\frac{360n}{365} \right) \right] \times \left[\cos(\phi) \cos(\delta) \sin(w_2 - w_1) + \left(\frac{\pi(w_2 - w_1)}{180} \right) \sin(\phi) \sin(\delta) \right] \quad (4)$$

and hot summers with relative humidity ranging from 51% to 83% and cold and rainy winters. Palestine has an insecure energy sector, which fully depends on nearby countries to compensate for its energy demands of the Palestinians people. In order to achieve sustainable development, residents of the West Bank need a lot of energy. However, a number of obstacles and issues prevent accomplishing this sustainability. A few of these are brought on by social, political, economic, and environmental problems.

This study's experimental dataset consists of 10 years (2014–2023) of hourly global solar radiation measured at the surface by Kipp and Zonen pyranometer that has an instrumental error of 5%. The Palestinian meteorological stations network owns and operate the radiometric station.

At a height of nine meters above the ground, the dataset was continually recorded from a station in the east Jerusalem village of Jabal Al-Mukabber. The geographical location of the radiometric station at the study site is shown in Table 1. Consequently, the long-term data contained sunshine duration, minimum and maximum surface air temperature. The readings are measured every three hours, with eight measures each day. Furthermore, the hourly global solar radiation long term dataset presents some of the null values (less than 70 records) and were replaced by the average of the nearest four values [20]. The daily averages, monthly and annual values are calculated from the dataset. The monthly mean of the daily extraterrestrial radiation, H_0 , can be calculated by [21].

Table 1. The radiometric station's geographic coordinates in east Jerusalem.

Variable	Value
Latitude	31.7555 °N
Longitude	35.2410 °E
Pyranometer height	9 m above earth surface
Altitude	720 m above sea level

The declination angle can be calculated by,

$$\delta = 23.45 \sin \left[\frac{360}{365} (284 + n) \right] \quad (3)$$

The average hourly extraterrestrial solar radiation must be determined in order to compute the clearness index by,

$$I_0 = \frac{12 \times 3600 G_{sc}}{\pi}$$

Where w_2 and w_1 are hour angles and $w_2 > w_1$. The monthly average of daily clearness index K_t can be computed using,

$$K_t = \frac{H}{H_0} \quad (5)$$

However, the monthly average hourly clearness index can be calculated by,

$$K_t = \frac{I}{I_0} \quad (6)$$

Where I is the hourly global solar radiation measurements.

According to the previous study performed by Okogbue et al. (2009) [22], the sky conditions (cloudy, partially cloudy, and clear skies) were utilized to statistically examine a region's K_t . On days without clouds, the weather is described as clear sky. Days with partially-cloudy skies are those where there are short clouds present and the solar radiation fluctuates quickly. In cloudy-sky conditions, the presence of clouds that can move across different air layers causes solar radiation to produce low values throughout the day. The description of K_t with respect to the sky conditions are presented by Govindasamy and Chetty (2018) [23] in Table 2.

Table 2. K_t values with respect to the sky conditions.

Description of Sky	Range
Clear	$0.7 \leq K_t \leq 0.9$
Partially cloudy	$0.3 \leq K_t \leq 0.7$
Cloudy	$0.0 \leq K_t \leq 0.3$

3. Results and Discussions

Solar radiation data has become crucial in measuring and forecasting energy production of photovoltaic systems. In this study, long-term global solar radiation, meteorological variables and derived parameters were explored and analyzed at hourly, monthly and annual basis.

Figure 1 introduces monthly average global solar radiation for Jerusalem during over 10 years period. As shown in the figure, the maximum value of solar radiation was found in June (28.68 MJ/m^2), while December recorded the minimum value (8.56 MJ/m^2). Overall, seasonal variation of global solar radiation is observed with summer months being higher than winter months.

The clearness index parameter (K_t), which measures how much solar radiation reaches the earth and defined by dividing surface radiation to extraterrestrial radiation, is explored. K_t can reveal information about the actual solar radiation. The scale values of K_t ranging from 0 to 1, based on the atmospheric conditions of the geographic coordinates of the estimated site, it can have a low or high value in both sunny and cloudy conditions. A K_t value close to 1 means that the light passing through

the atmosphere reaching the earth without any reflection,

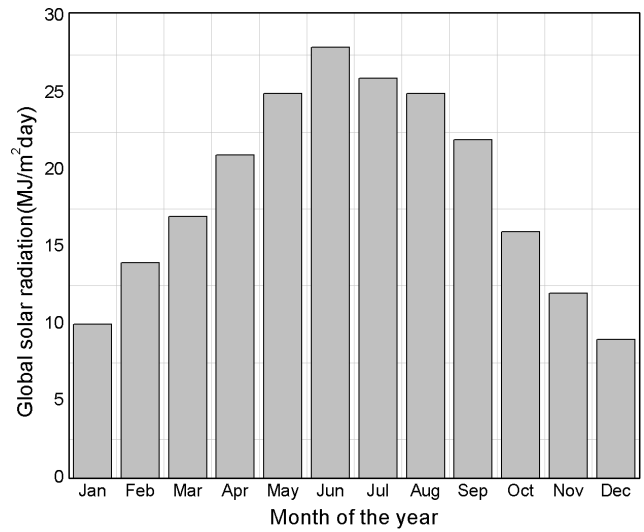


Figure 1. Variation of monthly average global solar radiation over 10 years (2014-2023).

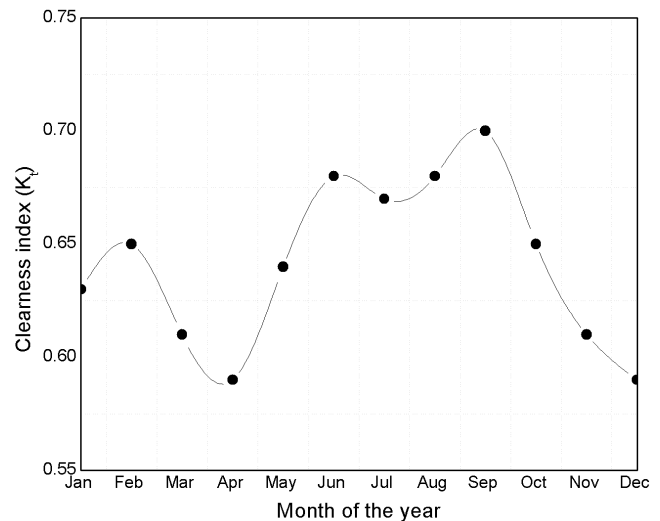


Figure 2. Monthly average clearness index variation over 10 years (2014-2023).

Figure 2 likely presents the average monthly K_t values over a 10 years period. On average, it can be noted that the monthly K_t values do not fluctuate significantly throughout the 10 years.

The seasonal variations in monthly average K_t show a maximum of 0.69 in September, where the minimum value ($K_t=0.58$) is observed in December. This decrease in K_t can be explained by the attenuation effects of increased cloud and water vapor during the rainy season. Due to the temporal variations in K_t and the meteorological variables, the seasons with relatively high K_t are characterized by more frequent clear skies due to a dominant high-pressure system. Similar seasonality was reported by Apeh et al. (2021) in Alice town

[24], South Africa, the obtained K_t values ranging from 0.51 in December to 0.66 in August.

The annual mean K_t ranging from 0.60 in 2014 to 0.68 in 2023, these values pointing to clear skies as recommended by Jo and Kang (2007) [25]. According to a similar study, "the reduction of global solar radiation is caused by increasing aerosol loading, which can cause decrement in K_t values" [26]. Consequently, this reduction in solar radiation would result in a "solar dimming" in this area; comparable results were observed in Jiangxi province-China from 2008 to 2016 [27].

According to Ohmura and Lang (1989), the fluctuations in K_t , in terms of long-term patterns, could be due to the combined effects of atmospheric variables or to the relatively distinct ways in which each of them influences K_t [28], decadal variations in global solar radiation at 24 locations in Europe were attributed to a change in cloud conditions. In Germany, research by Liepert (1994) [29] indicates that aerosols were a main factor in observed changes in global solar radiation. This finding suggests that the long-term K_t trends are dependent on the spatial and temporal variability of atmospheric properties.

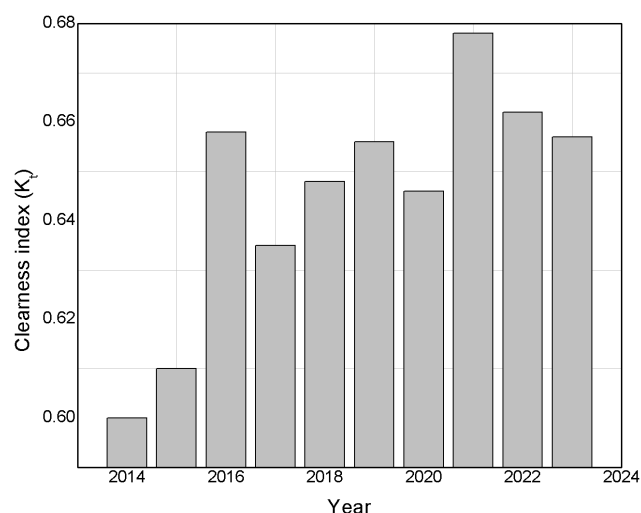


Figure 3. Annual average clearness index variation over 10 years (2014-2023).

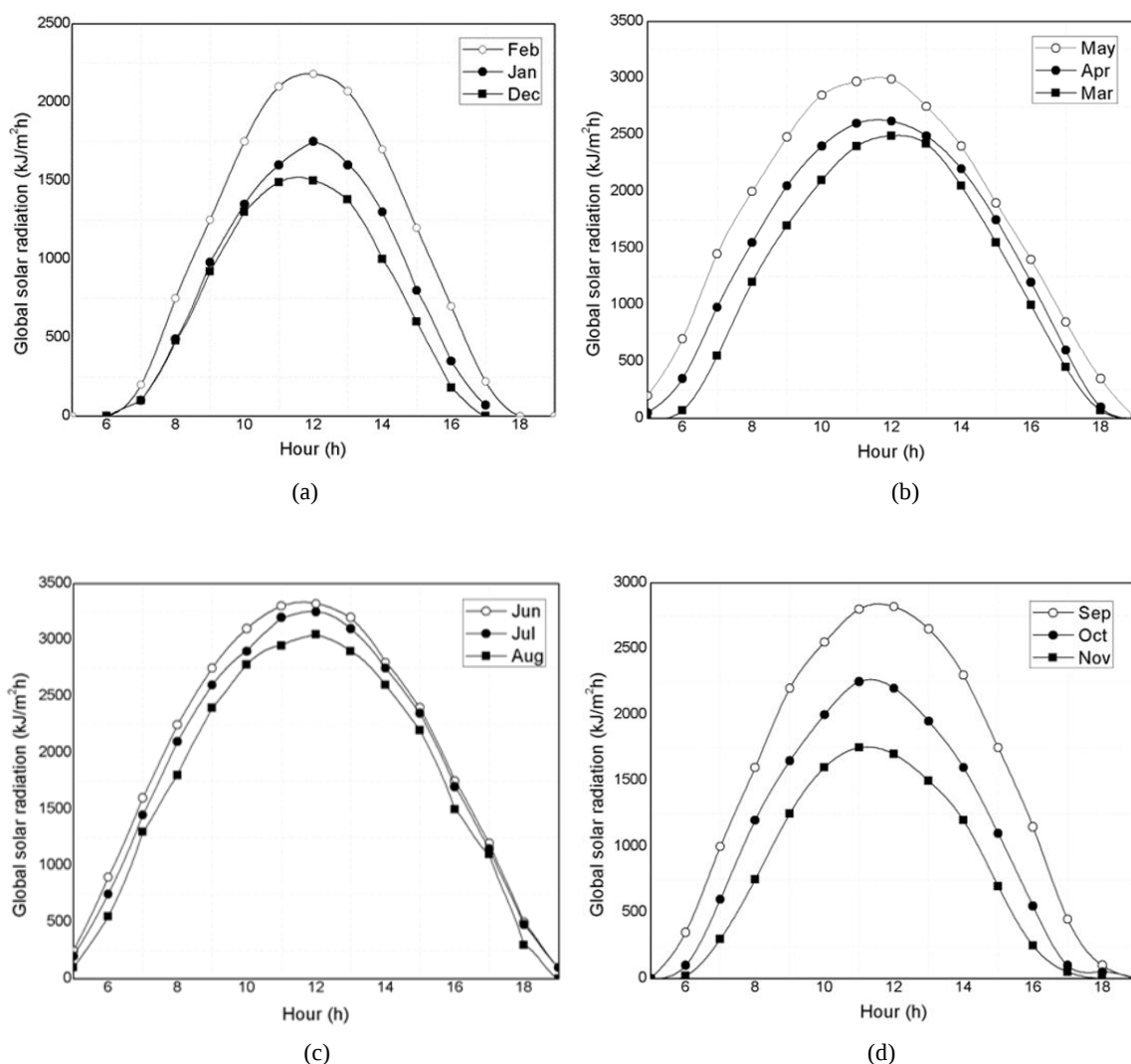


Figure 4. Hourly global solar radiation distribution by season for winter (a), spring (b), summer (c), and autumn (d) over 10 years (2014-2023).

In order to investigate seasonal variations, the dataset was divided according to seasons of the year. Figure 4 (a to d) shows the distribution of the hourly measurement results of global solar radiation by summer, autumn, winter, and spring seasons. It is evident that the highest value was recorded at 12:00. Furthermore, if the distribution of solar radiation throughout the day is considered, it reaches a symmetrical value around midday and begins to decline after that. This is because the K_t has lower values during the hours surrounding sunrise and sunset. At the same time, K_t reaches its peak values during solar noon. This is because, at solar noon, the solar radiation beam will travel shorter distance through the atmosphere than it would at sunrise. Consequently, as the solar radiation beam passes through the atmosphere, it will experience less reflection and scattering.

Figure 4 shows that during solar noon, global solar radiation reaches its highest recorded values, peaking at 3320 kJ/m² h. While the winter months (December-February) provide the lowest long-term solar radiation values, with De-

cember recording 1530 kJ/m² h. The seasonal global solar radiation experiences its peak levels during summer months (June-August) and the lower values during winter months (December-February).

To clarify the seasonal variations of global solar radiation, the hourly K_t frequency distribution for each season was examined and presented in Figure 5. It was found that hourly K_t values ranged from 0.21 to 0.8 throughout the entire study period. The summer months have the highest hourly K_t values, with $0.65 < K_t < 0.75$ (%75). The lowest frequency distribution is found to be in winter season, with $0.65 < K_t < 0.75$ is %33. As a result, clear days ($K_t > 0.70$) occur frequently throughout the year. However, using the weather classification recommended in Table 2, the three sky conditions apply to Jerusalem, with clear and partially-cloudy days being predominant. The fact that similar conditions were noted for the whole study period—including the winter months—makes these studies significant. This result shows that Jerusalem has reasonable potential of solar radiation when compared to other regions in the world.

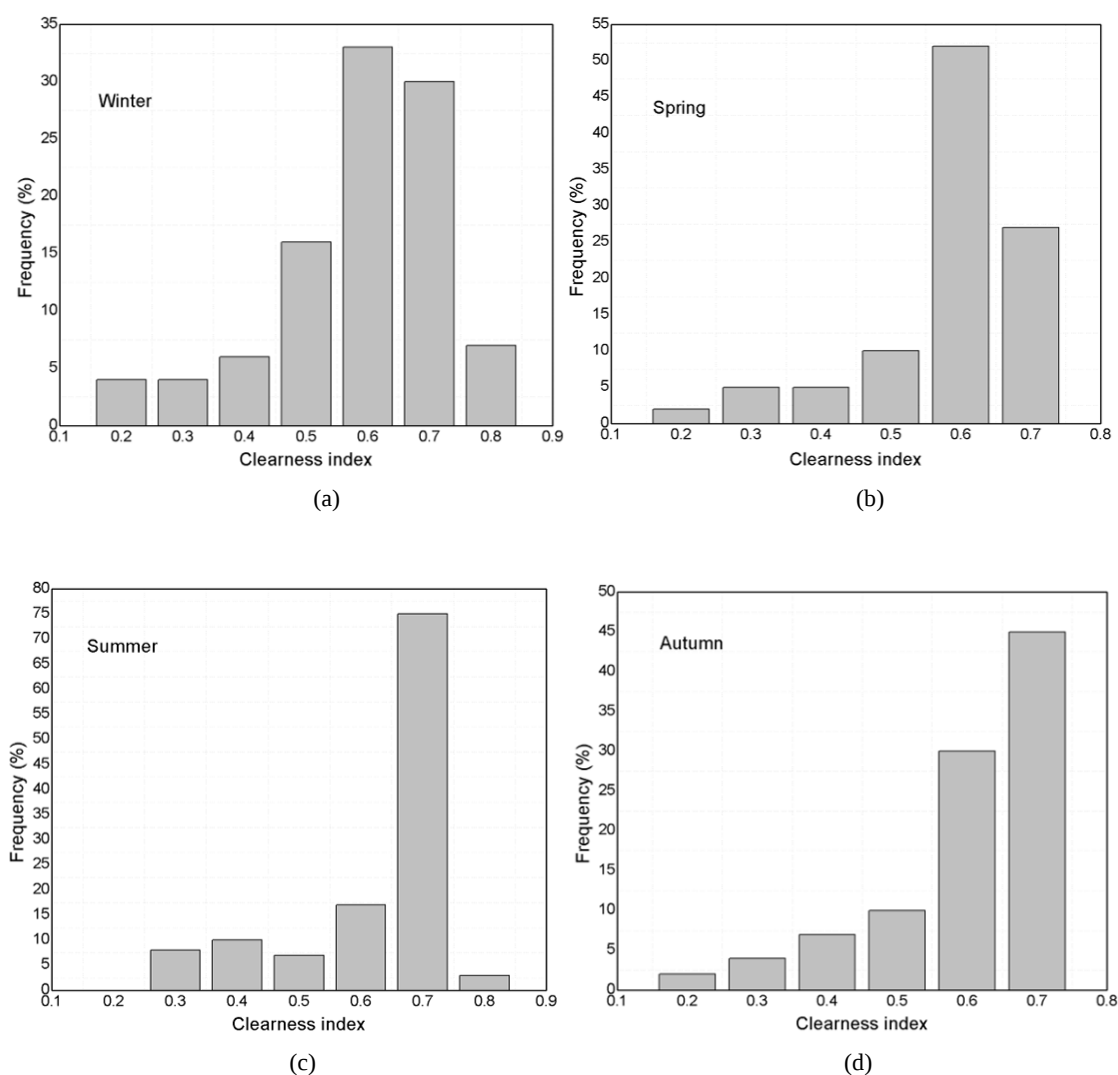


Figure 5. Hourly clearness index frequency distribution by season for winter (a), spring (b), summer (c), and autumn (d) over 10 years (2014-2023).

The annual average global solar radiation variations throughout the study period are typically presented in Figure 6. The 10 years-average global solar radiation have been calculated to determine variations and trends, also, a linear regression was used to fit the data. As observed, a general upward trend started from 2014 and continued up to 2023 with an increment of approximately 0.1% of global solar radiation between the maximum and minimum values which is consistent with the literature [30]. Also served in Figure 6, global solar radiation tends to increase from 2014 to 2021. Moreover, it is observed that there is a period of increment of every 3 years from 2014 to 2019. The maximum and minimum annual average global solar radiation values are observed in the year of 2021 and 2014 with 19.81 MJ/m² and 17.72 MJ/m², respectively. This result is completely consistent with the annual variation of the K_t presented in Figure 3.

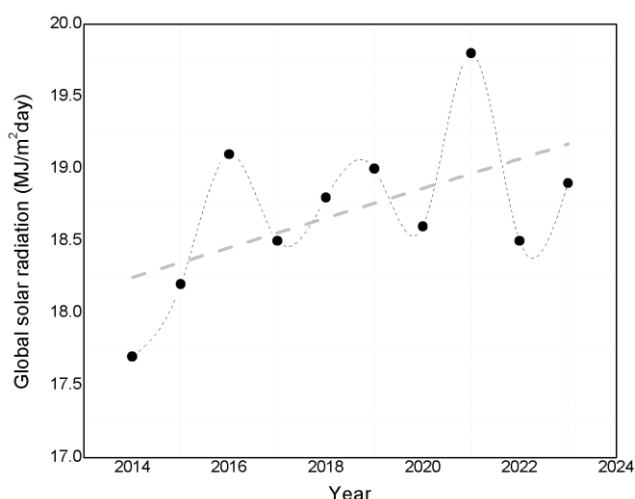


Figure 6. Annual average of global solar radiation variation over 10 years (2014-2023).

To better comprehend the situation in Jerusalem, Table 3 provides global radiation values for different regions of the world [31]. The annual average of solar radiation in Jerusalem of the entire period (2014 to 2023) is 18.67 MJ/m²day. Given that Jerusalem has one of the highest levels of solar radiation in the world, the city has a great and promising potential to generate solar energy, which essentially amounts to a national resource that is just waiting to be fully exploited.

Table 3. Yearly average global radiation for different cities in the world.

City	Yearly average global radiation (MJ/m ² day)
Amman, Jordan	20.51

City	Yearly average global radiation (MJ/m ² day)
Berlin, Germany	9.81
Paris, France	10.24
London, UK	9.31
Cairo, Egypt	19.92
Hong Kong	13.52
NY, USA	14.07
Jerusalem, Palestine	18.67

Surface air temperatures have their origin and strongly correlated with global solar radiation. The monthly mean, maximum, and minimum surface air temperature variations in Jerusalem are depicted in Figure 7. Overall, higher values are observed in summer months than those values in winter months. Moreover, August has the highest monthly maximum and minimum air temperature readings, at 29.1 °C and 17.3 °C, respectively, whereas, the maximum average value 23.1 °C is observed in July, while, the minimum value is 4.1 °C in January.

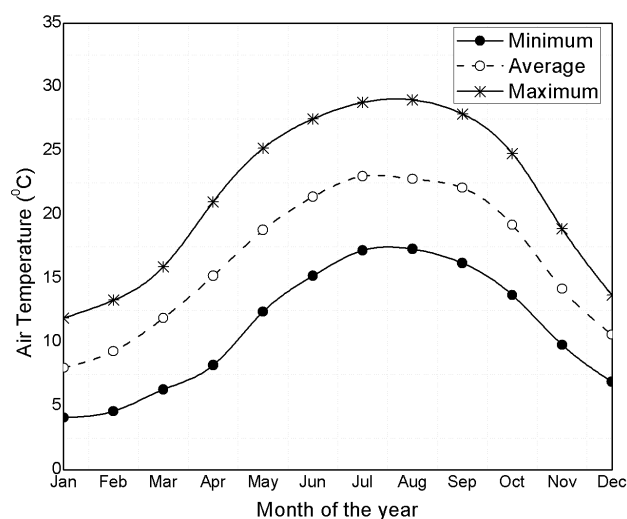


Figure 7. Monthly mean, maximum and minimum air temperature variations over 10 years (2014-2023).

Figure 8 shows a comparison between the monthly mean surface air temperature and the monthly mean global solar radiation. The surface air temperature is 21.4 °C in June, when global solar radiation reaches its maximum value of 24.1 MJ/m²day. This value is below the highest monthly mean temperature 24.92 °C that was recorded in July. Furthermore, the trend curve for the monthly variance in the average air temperature is identical to that of the global solar radiation.

The yearly temperature cycle, which shows a significant relationship between solar energy and air temperature, can be used to illustrate the systematic variation in incoming solar radiation over the course of a year.

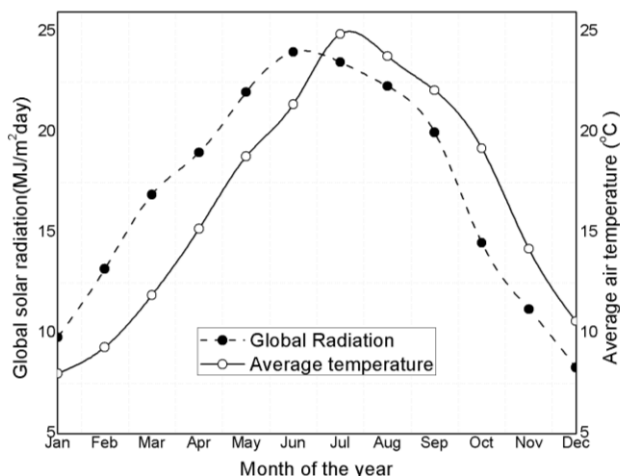


Figure 8. Monthly mean surface air temperature and monthly mean global solar radiation.

For 10 years period (2014-2023).

Figure 9 shows the average daily sunshine duration in Jerusalem throughout the year. It has been noted that the amount of sunshine each day ranges from 2.11 to 13.82 hours. The day 18th, which corresponds to January has the lowest daylight duration, while the 175th day which corresponds to June has the highest value. Additionally, it is observed that summer months, particularly June to August, have longer sunshine durations, whereas winter months have shorter values. It is found that the dataset average annual sunshine duration is 3007 hours. In comparison with the Mediterranean region, similar results were obtained by Pashiardis et al. (2023) [11] in the island of Cyprus. As displayed in figures 4, 8 and 9, the monthly variation of air temperature, solar radiation and sunshine duration provides strong relationship. In winter months, the sunshine hours were lower and the earth received the least solar radiation due to an oblique incident of the sunlight and optically thick low cloud; as a result, the temperature values was also low. Consequently, the highest sunshine hours in summer months, clear and sunny days, made the earth surface to receive the maximum solar radiation which lead to high temperature values. This strong seasonal variation of solar radiation and air temperature was also reported in Amman, Jordan [32] and Ankara, Turkey [26].

Figure 10 shows the variation in the annual average values of the sunshine duration from year to year. It was observed that with the exception of 2016 and 2021, which had the highest annual sunshine duration hours, there was little variation noted across the 10-year. The years 2021 and 2014 had the longest and shortest annual sunshine durations, at 3153

and 2755 hours, respectively. This outcome is consistent with the findings shown in Figures 3 and 6. When sunshine duration and solar radiation records are compared, the primary finding is that the latter exhibits greater signals during the summer, with an apparent rise in June, July and August and a stronger reduction in winter months.

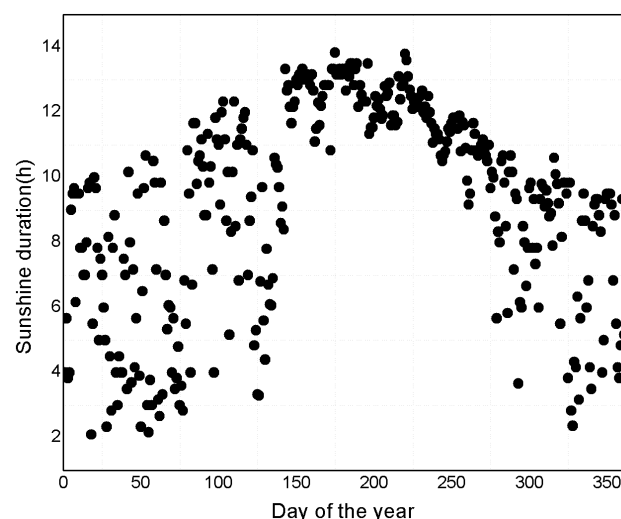


Figure 9. Jerusalem's daily average sunshine duration over 10 years period (2014-2023).

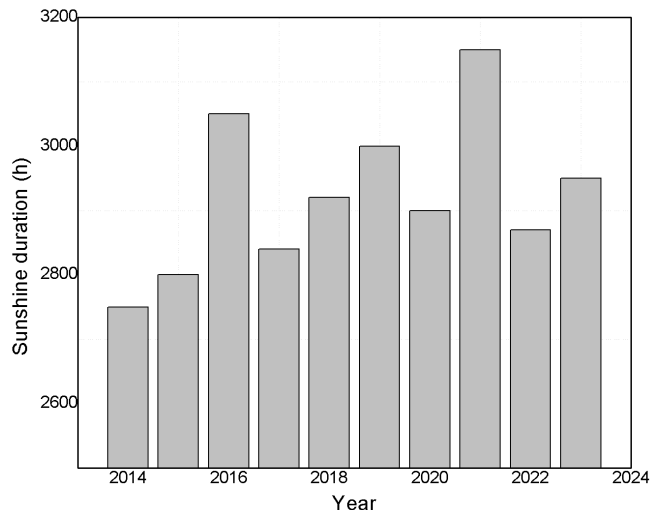


Figure 10. The annual average of the sunshine duration in Jerusalem.

Figure 11 displays a scatter plot of K_t versus monthly average global solar radiation. It can be noticed that the points fall along the diagonal line, hence indicating a strong positively linear correlation over the years. In comparison with Tables 2 and 3, the values presented in this figure confirms that Jerusalem sky condition has characteristics of lower partially cloudy days and more clear skies. Given that clearness index is a strong indicator of solar radiation in Jerusalem.

To sum up, this study can be considered as a reference to the other Palestinian cities since the spatial variability of global solar radiation is very small, which enables decision makers to encourage scientists, researchers and engineers in the Palestinian territories to exploit and develop photovoltaics and solar thermal projects, thus, the use of fossil fuels can be reduced using such energy as well as reducing the dependence of energy supply from other countries.

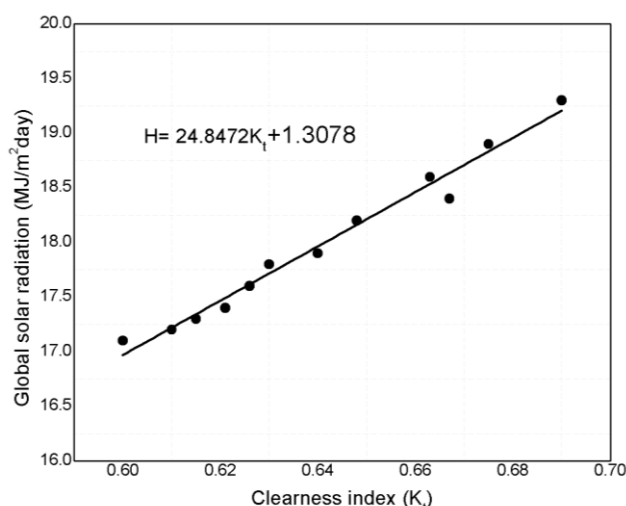


Figure 11. Correlation between clearness index with the corresponding values of monthly average global solar radiations over 10 years period (2014-2023).

4. Conclusion

This work evaluates the potential of long-term solar radiation (2014-20123) in Jerusalem, Palestine. The highest monthly average global solar radiation was 28.68 MJ/m^2 in June, while the lowest value was 8.56 MJ/m^2 in December. The monthly average clearness index ranges from 0.58 to 0.69. Consequently, the clearness index frequency distribution indicates that clear skies are dominant in Jerusalem. The exploration of seasonal variations in global solar radiation revealed that summer months had the highest hourly global solar radiation values ($3320 \text{ kJ/m}^2\text{h}$ in June) and lower in winter months ($1530 \text{ kJ/m}^2\text{h}$ in December). The average daily sunshine duration ranges from 2.11 to 13.82 hours. Strong positive relationship of solar radiation versus clearness index providing that clearness index is a perfect indicator of solar radiation. Finally, the analysis of long-term global solar radiation values elucidates its status in Jerusalem and provides strong feedback for those who invest in solar energy in the region. Compared to other regions in the world, Jerusalem has a huge and promising potential to produce solar energy because it has one of the highest levels of solar radiation in the world. Future studies should focus on the analysis of energy consumption and incorporate other techniques such as machine learning models to estimate solar radiation in this region as well as the comparative analysis between ground measurements and satel-

lite-derived data.

Author Contributions

Husain Alsamamra: Conceptualization, Data curation, Formal Analysis, Methodology, Resources, Software, Writing – original draft, Writing – review & editing

Conflicts of Interest

The authors declare no conflicts of interest.

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