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Research Paper

Relationships between daily solar irradiance and maximum temperature in Iraq

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ABSTRACT

This study investigates the relation between daily solar irradiance (SI) and maximum air temperature (Tmax) over six cities in Iraq (Basra, Shanafiya, Baghdad, Rutba, Kirkuk, and Shakhan) using NASA POWER data for the period 2014-2023. Results revealed that in the arid southern provinces such as Basra, the annual mean SI exceeds 5.6 kWh $m^{-2}day^{-1}$ and Tmax frequently exceeds 48°C during the summer months while in the northern provinces lower SI and Tmax values were observed. The seasonal variation indicated peak values of SI during June while peak values of Tmax were observed in July-August. A strong relationship between SI and Tmax were obtained with R^2 of 0.75 to 0.82 at different locations.

Keywords: Solar irradiance, Maximum temperature, POWER data, Correlation, Regression, Iraq

Solar irradiance (SI) and maximum air temperature (Tmax) are the key meteorological variables in the design and performance of solar energy systems, human health, and the ecosystem. The former is the amount of sunlight that hits a unit area in a limited time (e.g., one hour), while the latter is the highest temperature recorded during a day at a given location. Both variables depend almost entirely on several factors such as time of day, season, weather conditions, and landscape (Al-Samarrai and Al-Jiboori, 2023; Odejobi *et al.,* 2024). Alternatively, the high variations of daily SI intensity and Tmax, especially during peak solar hours, are proportionally related to photovoltaic power output, while higher Tmax not only reduces solar panel efficiency (Daut *et al.,* 2012), but also degrades solar cell materials. In addition, the extreme values of these variations were dominated in arid regions (Ben Amara *et al.,* 2024), which has a negative impact on plant growth (Mina *et al.,* 2015), evapotranspiration rates, increased heat-related illnesses such as heat stroke, increased energy demand, and water scarcity in reservoirs and rivers (Mendoza, 2004; Mahdi *et al.,* 2024).

Ibrahim *et al.,* (2012) estimated solar radiation from temperature in Perlis northern Malaysia and found a strong relationship between these variations. Lawin *et al.,* (2019) evaluated the variability and projected trends of SI and temperature in the East of Burnndi using historical and projected data from regional climate model. It was found that the increase in temperature and decrease in solar radiation in the last decades of the 20th century and the excess of SI coincided with the dry season, while in the future, upward trends in temperature are expected (Lawin *et al.* 2019). Tan *et al.,* (2024) determined the appropriate meteorological parameters for solar energy prediction using Pearson correlation coefficient, and they found that these parameters are air temperature, cloud opacity, global tilted irradiance, relative humidity, and zenith angle, which correlated with solar irradiance, Sarawak using machine learning. The present study has been proposed to study the spatial variations of daily solar irradiance and Tmax over the period (2014-2023) and to established the relationship between SI and Tmax over Iraq.

MATERIAL AND METHODS

Study area

Iraq, a country in Middle East and the southwestern Asia, is located between latitudes 29° and 38° N and longitudes 39° and

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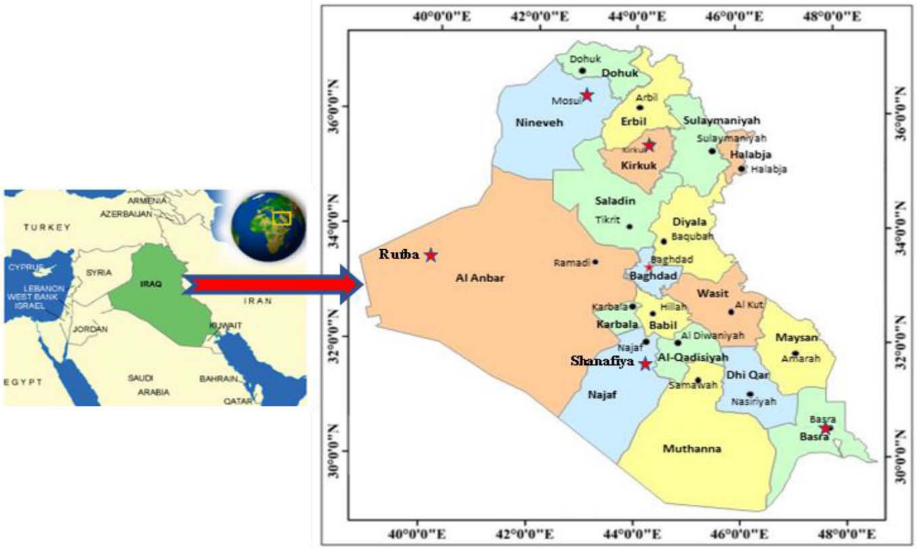


Fig. 1: The study area of Iraq including six selected cities

48° E (Fig. 1). There are four physiographic regions: the alluvial plains of the central and southeastern, Al-Jazīrah, an upland region of the Tigris and Euphrates, and deserts in the west and south, and the highlands in the northeast. Due to the strategic position between the subtropical desert belt and temperate zones, it significantly influences its climate characterized by an arid to semi-arid climate with significant solar irradiance and high maximum temperatures (Al Rukabie *et al.,* 2024).

Dataset source

The daily data of solar irradiance (SI, kWh $m^{-2}day^{-1}$) and maximum air temperature (Tmax, ^{0}C) used in this study were sourced from NASA POWER portal (https://power.lars.nasa.gov) database for the period from 2014 to 2023. Data available on a grid basis with a daily time resolution and a spatial resolution of about 1° by 1° globally were obtained for Iraq locations. Tmax was typically derived from MODIS (Moderate Resolution Imaging Spectroradiometer) satellite observations combined with ground-based weather station data. The accuracy of both, NASA POWER data were typically good for large-scale studies, especially in regions with consistent satellite coverage and available ground data (Jed *et al.,* 2022; Tan *et al.,* 2024). However, there may be localized errors or uncertainties, especially in areas with complex topography, cloud cover variability, or unusual weather patterns.

Methodology

The daily means of SI and Tmax records for each month of the calendar year over the study period (2014-2023) were separately calculated for all six cities (Basra, Shanafiya, Baghdad, Rutba, Kirkuk, and Shakhan). The monthly means for IR and Tmax were also calculated with standard deviation (SD). The linear regression equation was used to study the relationship strength between the two variables. It assumes that the relationship is linear, meaning SI can be expressed as a straight-line that fits that data (Al-Jiboori *et al.,* 2020; Wahab *et al.,* 2022).

$$Y = \beta * X + \beta_o$$

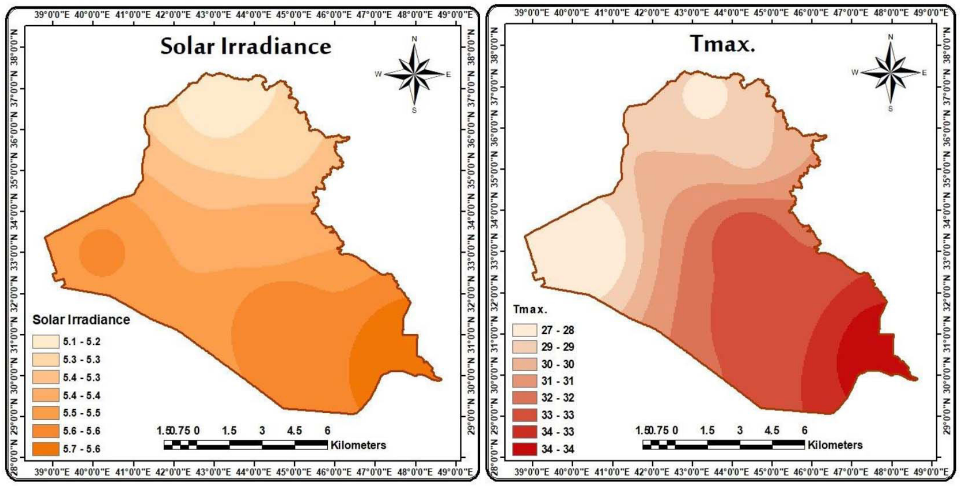
where β_o is the intercept of the regression line, and β is the slope of the regression line that represents a rate of change. These constants were determined from the values of solar irradiance and Tmax through Origin program. R^2 (coefficient of determination**)** - goodness of fit - was used to measure how well the above model fits the analyzed data. When the R^2 closes to 1, most points are close to the line of best fit and the observations are close to the model's predictions, while the R^2 approaches ٠, many points are far from the fitting line.

Finally, based on the monthly means SI and Tmax, their annual means were calculated by summing the monthly values divided into 12. Spatial analysis maps of Tmax and SI variations across Iraq's provinces were generated using Kriging technique for interpolation continuous maps from the scattered data points through GIS software to visualize spatial distribution based on the spatial correlation of nearby data points.

RESULTS AND DISCUSSION

Spatial distribution of solar irradiance (SI) and maximum temperature (Tmax)

Fig. 2 shows the spatial distribution of annual SI (kWh $m^{-2}day^{-1}$) and Tmax (°C) over Iraq during 2014-2023. There is a clear north-to-south gradient, with irradiance increasing as we move southward. The annual means of SI values ranged from 5.1 to 5.7 kWh $m^{-2}day^{-1}$, indicating relatively high solar potential across Iraq. The darkest shades (5.6–5.7 kWh $m^{-2}day^{-1}$) are concentrated in the south, particularly in Basra and adjacent areas. This reflects flat desert terrain and clear skies and minimal atmospheric obstruction. The lightest shades (5.1–5.3 kWh $m^{-2}day^{-1}$) were dominated, indicating lower solar irradiance in northern Iraq. A moderate range of solar irradiance (5.3–5.5 kWh $m^{-2}day^{-1}$) is observed in the central part of Iraq (Fig. 2a).



(a) **(b)**

Fig. 2: The spatial distribution of annual mean (a) SI (kWh $m^{-2}day^{-1}$) and (b) Tmax (°C) over Iraq

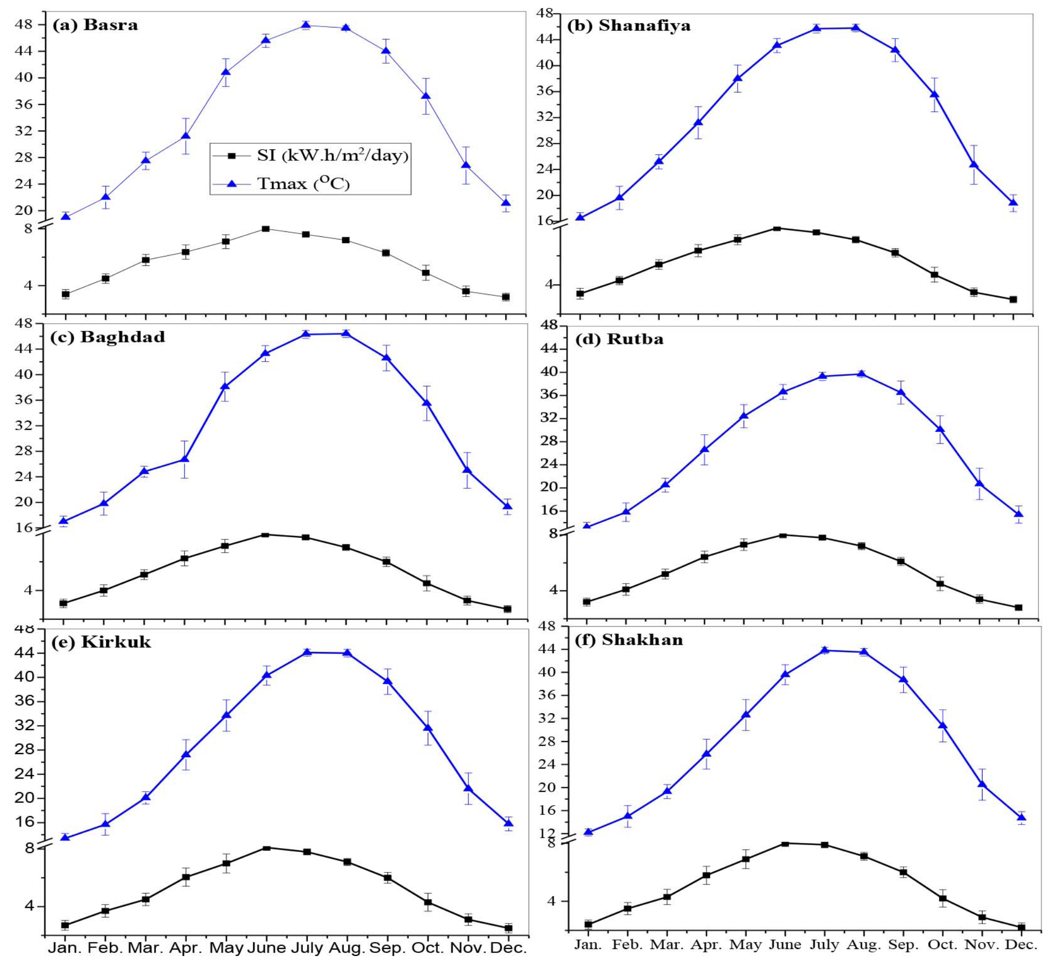


Fig. 3: Monthly variation of means of daily solar irradiance and Tmax at selected cities

Fig. 2b illustrates the map of spatial distribution of the annual mean Tmax (°C) across Iraq for the same period, which categorized into temperature ranges and highlights distinct regional variations in Tmax. The temperature gradient clearly displays a south-to-north decline, which aligns with Iraq's geographical and climatic patterns. The southernmost regions, including Basra, exhibit the highest Tmax values, ranging from 34 to 34.5°C. This area is characterized by its arid climate and proximity to desert zones, which amplify heat intensities. Moving northwards into the central parts of the country (Shanafiya and Baghdad), Tmax

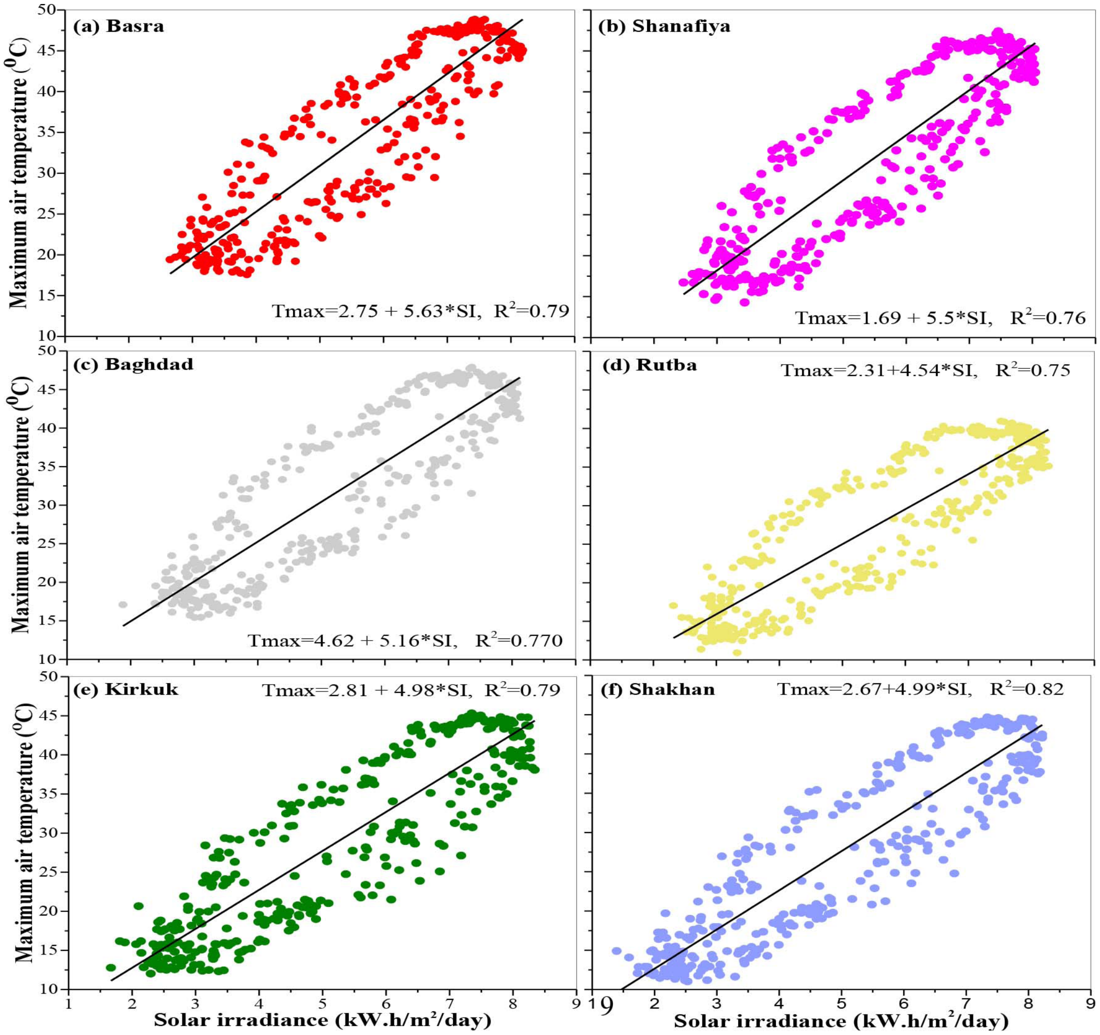


Fig. 4: The relationships between annual daily solar irradiances and maximum temperatures at the six Iraq's cities over the period (2014-2023)

decreases slightly, ranging between 31 and 33°C. This transition indicates a moderate influence of elevation and climate variation. The highland regions located in north and west parts represented by Rutba, Kirkuk and Shakhan show the lowest Tmax values, ranging from 27 to 29°C.

Seasonal variations of SI and Tmax

The mean monthly SI and Tmax over all six selected cities are presented in Fig. 3. The pattern of variations of both the parameters (SI and Tmax) seem to be almost similar. The variations are similar across cities, except for the peak SI, which does not always coincide with the peak Tmax due to the time required for heat accumulation at the Earth's surface, atmospheric dynamics, and local climate conditions. Fig. 3 shows that June has the highest SI, but July and August have the highest Tmax due to thermal inertia. The monthly time lag in the relationship between SI and Tmax refers to the lag in temperature response to changes in solar radiation. The Tmax variation across the cities is fair with increasing in southern and middle parts with an average of 44 °C to lower values reaching about 38 °C in northern part. Of course, this variation caused mostly by the differences in elevation. Owing to Baghdad is medium density urban (Haraj and Al-Jiboori, 2019) with a significant high population, it experiences high temperatures approach Basra province. While the variations in SI and Tmax are higher in October, November, February, April across all provinces. In winter, the monthly means for SI and Tmax showed the lowest values during the year with gradual decrease from the south 3.3 kWh $m^{-2}day^{-1}$ and 20 °C to north (Shakhan) 2.3 kWh $m^{-2}day^{-1}$ and 14.7 °C. The solar irradiances were experienced highest values in June and July months starting from 7.3 to 8.2 kWh $m^{-2}day^{-1}$, which were associated with also highest maximum temperature reaching 49 °C in Basra, while the lowest values of both daily mean SI and Tmax were at December and January with ranges of 1.5-4 kWh $m^{-2}day^{-1}$ and 11-24 °C respectively over Iraq. The analysis of the monthly results among the cities indicated that the peak SI values were observed in the month of June over all the locations while the peak values of Tmax reached in the months of July and August. Similarly, the lowest values of SI were observed in December while the lowest Tamx values were observed in January. Thus, a time lag of one-two months between SI and Tmax.

There are several underlying factors influencing the relation nature for SI and Tmax, for example, regions with high SI typically experience more sunny days, which leads to higher Tmax due to prolonged solar heating, the desert-dominated south absorbs more solar irradiance, intensifying Tmax, and higher elevations in the north contribute to cooler Tmax and lower SI due to increased cloud cover and diffuse radiation.

Relationship between SI and Tmax

To study the correlation strength between SI and Tmax, the regression model was used to fit the pair data points for all months and cities. The scatter plots in Fig. 4 show the relationship between SI and Tmax for two monthly time lags. The coefficient of determination is also displayed on each plot, indicating how well changes in SI explain variations in Tmax with monthly lags. After obtaining the best lines and based on these data, the constants βo and β were calculated in addition to R^2. The results of these constants were also reported on Figs. 4a-f with full equations, which show that the intercept value was the largest in Baghdad. The intercepts and slopes at all cities have positive signs, which indicated the upward linear relations, but with different in their intensity according to geographic location. In southern Iraq represented by Basra, the steep slope was significant with largest value of 5.6 and very good correlation R^2=0.79, as shown in Fig. 4a. In north of Iraq, Shakhan and Kirkuk showed approximate the same values of slope with an average of 4.98 with a very good R^2 (~0.8). In the middle of Iraq (Shanafiya and Baghdad) the slope and R^2 were approximately equal with an average value of about 5.3 and 0.77, respectively (see Figs. 4b and c). In Rutba, Fig. 4d shows the lowest values of upslope with a good correction of R^2=0.75. It should be noted that the R^2 values are between 0.75 and 0.82 in all cities and cannot be higher due to the high dispersion of the annual daily SI and Tmax data. This is due to the monthly asymmetries of the two curves of SI and Tmax in all cities, which increase the possible errors. Additionally, in winter and spring seasons, the activities of weather systems including clouds, rains, high relative humidity, sometime snow, and dust storms are more frequently in Iraq (Muter *et al.,* 2024; Deagan and Al-Jiboori, 2023), which are blocking the solar irradiance reaching the Earth's surface. It is worth noting that the raised air pollution levels in urban cities could be reduced the solar irradiance with about 10% in cities, especially pollution caused by traffic emissions (Anad *et al.,* 2022; Gómez *et al.,* 2023; Nasser *et al.,* 2024). However, the two variables solar irradiance and maximum temperatures were not perfectly linear due to these moderating factors.

CONCLUSIONS

This study highlights a clear monthly and regional variation in daily solar irradiance (SI) and maximum temperature (Tmax) across Iraq from 2014 to 2023. A direct relationship between SI and Tmax was observed in all studied cities with a highest correlation (R^2=0.82) found in Shakhan. Tmax always peaks after SI due to the two-month lag (July and August), which prevents the SI-Tmax relationship from improving. The north-south gradient in both variables reflect higher SI and Tmax in the southern regions, particularly in Basra, with an annual mean Tmax of 34.5°C and SI of 5.7 kWh $m^{-2}day^{-1}$, signifying its high solar potential. Central areas show moderate values, while northern and western highlands exhibit the lowest Tmax and SI. Overall, Iraq experiences significant solar energy potential, with regional differences influenced by geographic and climatic factors.

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Authors contribution**: A.A Zahraa:** Conceptualization, Methodology, Data Curation, Formal analysis, Visualization, Writing - Original Draft, Writing - Review & Editing; **JS Abd Al Rukabie**: Conceptualization, Methodology, Data Curation, Formal analysis, Visualization, Writing - Original Draft, Writing - Review & Editing; **MH Al-Jiboori**: Writing - Review & Editing, Supervision; **MH Khaleel**: Methodology, Conceptualization, Formal analysis, Writing - Original Draft, Writing - Review & Editing.

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