Al-Muthanna J. For Agric Sci Online ISSN:2572-5149
Print ISSN: 2226-4086
Vol. 13 , Issue 1. 2026

https://muthjas.mu.edu.iq/ http://doi.org/10.52113/mjas04/13.1/32

Performance and Efficiency of Solar-Powered Irrigation Systems in Iraq a Field and Numerical Evaluation in Two Climatically Distinct Regions

Mohammed Saeed Abduljaleel Abdulmojib1[a],

[a]*Urmia University, Renewable Energy engineering, Iran*
**Corresponding author E-mail: mohammedsabd2@gmail.com*

Abstract

Solar powered irrigation systems are becoming popular for overcoming energy constraints and for better management of water in dryland and semi-dryland agriculture. In Iraq, differences in climate from location to location can materially affect the field performance of these systems, even when the units have been designed the same. This research investigates the functionality and efficiency of solar powered irrigation system two identical installations located at the agricultural extension farms of the Directorate of Agricultural Extension and Training, Iraqi Ministry of Agriculture, set up in Mosul (Nineveh Governorate) and Karbala Governorate as two climatically different sites. Every installation has a 15-kW photovoltaic array (with 26 modules of 580 W power each) driving a 15 hp Lorentz surface pump. An operational record assembled over a winter monitoring window (November–January) was used in a combined field–numerical framework. The efficiency, power losses, and hydraulic operating conditions of the system are quantified using a numerical analysis, while daily and hourly water discharge, effective operating hours and electrical energy produced are field observations. Although the configurations of both sites are identical and their modeled efficiency indicators are comparable, the Karbala site managed to produce greater water output during the winter season. This increased water output, on average, exceeded that of the Mosul site by about 10-15%. The betterment that has been observed can mostly be put down to better sun received and longer effective hours of working in the desert in the south. The results in this paper show that site selection and climate are key drivers of practical solar irrigation performance in Iraq, even if system design parameters are fixed.

***Keywords*: :** *solar-powered irrigation; photovoltaic pumping; climatic variability; system efficiency*

1. Introduction

Farmers in the regions suffering from unreliable grids and rising costs of fuel are increasingly using solar energy to meet their irrigation pumping needs. Correctly designed solar irrigation systems can significantly reduce the use of diesel and electricity from the grid, stabilize the water delivery reliability and enhance the operational resilience of farm production systems. [1,2]. In practice, though, site-specific meteorology and seasonal variability dictate photovoltaic (PV) pumping performance. Daily and intra-day variations in solar irradiance and ambient and operating temperature affects the electrical output of PV and motor-pump operating stability, delivered flow rate, and its cumulative daily water production. As a result, performance assessments based on the field are necessary because design-point and nominal calculations might diverge from actual operation from month to month and across climatic zones. [3,5,7].

In dry and semi-dry countries, environmental stresses (dust and soiling) due to climate sensitivity can reduce the effective irradiance on the module surface, thus degrading its power yield. Iraq presents a compelling case for this issue because dust events and dust deposition are identified as a material limiter to PV performance, as well as a source of seasonal variability in energy yield. Considering real-world site conditions will provide realistic efficiency and output estimates as well as transferrable design guidance. [8,10].

In Iraq, the application of solar-driven pumping has grown in recent years. This extension has covered agricultural extension farms controlled by the Directorate of Agricultural Extension and Training at the Iraqi Ministry of Agriculture. Despite this, much of the literature focuses on conceptual design, component-level optimization, or short monitoring windows. There aren't many studies that give integrated, site-comparable assessments that systematically measure the field together with a numerical modelling framework that quantifies efficiency-related losses and operational constraints under realistic irrigation schedules. [2,6,7].

Distinct climatic conditions characterize Iraq's northern regions and central–southern belt. Notably, studies indicate variations in PV pumping performances in these two zones. So, we need to isolate the effect of installation location to be able to support planning based on evidence, which improves deployment decisions to reduce performance shortfall. It certainly aligns with wider assessments, e.g., that the sustainability value of PV systems does not just stem from nominal emission advantages but also realistic operation, maintenance and environmental exposure. [1,2,9].

So, this study assesses and compares two similar solar-powered irrigation systems installed at two Iraqi locations with different climates, namely Mosul and Karbala Governorate. A field-integrated numerical framework is applied over a specified winter operating period to estimate discharge performance, operating hours, energy generation, efficiency-related losses, and to ascertain the degree to which climatic location alone causes the observed differences in delivered water output under similar operational conditions [3–5,7].

2. Study area and system description

The field of study was carried out in the two agricultural extension farms owned by the Directorate of Agricultural Extension and Training (DAET), one of the formations of the Iraqi Ministry of Agriculture. The northern region (Mosul, Nineveh Governorate) and the central–southern desert region (Karbala Governorate) were chosen by the farms to demonstrate the climatic differences. The choice of these sites enables a fair comparison of system performance under diverse climatic conditions while having the same technical configuration.

2.1. Study sites description

The Al-Hamdaniya Agricultural Extension Farm (Mosul, Nineveh Governorate) is the site representing northern Iraq. The winter operation at the site usually experiences lower irradiance and more numerous cloud/rain events relative to the central–southern belt. The second site is the Desert Agricultural Extension Farm (Karbala Governorate), which represents an arid region that has higher solar irradiance in winter and longer sunshine span. As a result, it tends to maximise the effective PV pumping hours per day. Due to the strong sensitivity of PV pumping systems to irradiance variability, such a two-site design is suitable for disentangling the climatic-location effect on operating hour and delivered water functionality under identical technical configurations [2,3,7].

2.2. Solar-Powered irrigation system description

Both sides had the same solar-powered irrigation systems in place so that differences in performance can be attributed largely to climate and location rather than component selection. Every system has a photovoltaic (PV) array of 26 monocrystalline modules rated at 580 W each with a total installed capacity of about 15.08 kW. The irrigation operation is carried out using a 15 hp Lorentz surface pump powered by the photovoltaic array. While the technical and hydraulic configuration of the systems were kept the same at both places, uniform methods were used. The specifications of module type, installed capacity, pump power, and mounting configuration are summarized in Table 1. The system architecture must remain unchanged to isolate the climatic effect on performance as per the recent studies on photovoltaic pumping. [2,3,7]. To maximize solar energy generation during the monitoring period, the tilt angle of the photovotaic array was adjusted according to local latitudes. The inclination selected close to site latitude in established fixed-tilt design practice helps to improve solar incidence and enhance seasonal energy yield. [8,9].

2.3 System Configuration and operating conditions

At both study sites, two solar-powered irrigation systems were installed by using similar mounting structures and operated on the same practical irrigation regime. The electrical and hydraulic configuration of the two installations was kept identical for a fair comparison in terms of PV module technology and number, total installed capacity, type and rated power of pump and pipeline layout for water supply. Table 1 summarizes the main system specifications.

Table 1: Technical Specification of the Components of Solar-Powered Irrigation System.

Component / Parameter	Technical Specification
Photovoltaic (PV) Panels	26 Monocrystalline Solar Panels
Individual Panel Rating	*W* 580
Total Installed Capacity	*kW* Approximately 15,08
Pump Type	Lorentz Surface Pump
Pump Rated Power	*hp* 15
System Configuration	Identical at both study sites
Panel Tilt Angle	Adjusted per site latitude for optimal incidence

The only parameter that was intentionally varied was the PV array tilt angle, which was adjusted according to the latitude of the two locations to enable maximisation of the incident solar radiation during the monitoring period. The latitude based fixed-tilt approach is generally used in PV system practice and optimization studies (the latest one focused on Iraq) show that optimum fixed (annual or seasonal) tilt is generally close to the latitude. Furthermore, seasonal adjustments are applied in practice which often involves increasing the tilt in winter for maximum solar gain.
As such, the specified installation location and its climatic boundary conditions (solar irradiance availability, ambient temperature profile and day-on-day weather variation), along with the latitude-dependent tilt setting, are the primary drivers of the differences in operational window, effective energy capture and field water output between the two sites, with system design and hardware ratings being constant.

3. Materials and Methods

Using the same modelling system with the same parameters for both systems, means performance and efficiency data for two identical systems in the field is available for comparison. Field monitoring estimated real water delivery and PV energy production, while numerical estimates were used to obtain hydraulic power, operating efficiency and performance indicators under the similar irrigation operating regime.

3.1 Field measurement methodology

Data collection for agriculture was carried out at both sites over a winter monitoring window of three months (November – January). The operation of the system was according to the irrigation schedule recommended for wheat crop cultivation to show agricultural operation, not continuous pumping. While the system was running, the recorded operational observations (PV electrical output and water discharge) were time-stamped which were adequate for constructing hourly performance profiles and daily totals at each site. The daily water output (m^3/day) was calculated by summing the discharge observations for each operating day, while hourly discharge profiles were estimated by grouping the recorded discharge values for each hour.
The criteria for effective hours were uniformly set up at both sites – an hour was counted as “effective pumping”, only when there was sustained pumping, i.e., when there was continuous non-zero discharge over the interval. Transient start/stop periods during the intervals and non-productive low-flow operation were not included. Before aggregation, all field records were checked for completeness and internal consistency (missing-day checks and nonphysical-value screening).

3.2 Numerical analysis method

The measured time series for the PV power and energy were used to calculate daily energy yield and to validate efficiency and comparison performance calculations. Initially, electrical output data were examined for continuity and consistency as well as for nonphysical values. To make sure electrical intervals of measure and hydraulic intervals of measure corresponded, missing or incomplete intervals were omitted from the efficiency calculations. The validated time series was temporally aggregated to yield daily and seasonal energy indicators.
The discharge, along with the operating head corresponding to the discharge under field conditions, was measured as an evaluation of hydraulic performance. The total dynamic head is equal to the system design and operating configuration, which includes static head plus the estimated friction losses in the pipe. Because both installations had the same hydraulic layouts, the same methodology was used in both sites to allow for comparison. The method reduces systematic favoritism when assessing performance variations between climate locations.
The standard expression was used to calculate the hydraulic power that is delivered to the pump water:

$$P\_h = \rho\, g\, Q\, H$$

According to this approach, the water density was constant (ρ) under winter conditions and the gravity 9.81 m/s^2(g). The flow rate (Q) was taken from field discharge measurements, and total dynamic head (H) referred to pumping operating conditions monitored through time.
The overall system efficiency measures the ratio of hydraulic power output to photovoltaic electrical input:

$$\eta\_sys = P\_h / P\_PV$$

Electric power supplied by the photovoltaic system to pump drive is known as P_PV. In order to assess the efficiency on an hourly and daily scale, hydraulic and electrical data were synchronized within the same time. The daily results were averaged throughout the entire monitoring period to calculate the seasonal efficiency indicators.

For the sake of comparability, we used the same computational procedure, assumptions and aggregation criteria at both sites to enhance the robustness of our insights. The performance differences observed were thus largely due to climate differenced, and not due to any methodological or numerical bias. Also, the sensitivity checks establish that reasonable alterations of discharge or head, within a reasonable range of measuring error, do not influence the comparative conclusions of the two places.

3.3 Performance indicators

A set of field-based and derived indicators were used to evaluate performance to reflect practical irrigation productivity and system energy efficiency in an operational environment. Using hydraulic and electrical data synchronously, these indicators were calculated and applied the same way in both sites for comparison:

1. Daily water output (m^3/day)

The daily water delivery was calculated by summing the measured discharge over the effective pumping period of each day. This indicator is the most important operational parameter from an agricultural point of view because it reflects the potential of the system to meet irrigation demand at the particular climatic condition of the site.

2. Hourly discharge profiles and peak hourly discharge (m^3/h)

To generate representative daily performance curves, time-resolved discharge data were aggregated at an hourly scale. Peak hourly discharge was identified for each operating day in order to determine the proportion of time that the system achieves and maintains nominal operating conditions. This indicator provides insight into system stability, midday performance, and the impact of solar resource variability on pumping behaviour.

3. Effective operating hours (h/day)

A consistent operational criterion applied at both locations allowed the definition of effective hours based on the sustained pumping operation. The only period considered as productive operating time was the time during which there was a continuous stable discharge. All transients, including start-up, shut-down and low flow, were excluded. This indicator shows the practical availability of usable solar energy for productive irrigation period.

4. PV energy yield (kWh/day)

The time series of the electrical output recorded the daily photovoltaic energy production. The useful solar energy potential available for the pumping system is an important indicator of hydraulic performance. Through aggregation of daily values over the monitoring period, seasonal energy availability was determined.

5. Overall system efficiency

The system efficiency was determined as hydraulic energy given to the pumped water and electrical energy obtained from the photovoltaic system. Hourly and daily calculation of efficiencies and their averaging offered representative seasonal value. This indicator makes it possible to compare the energy conversion performance of the two sites and helps in interpreting climate influences on operation.

The integrated use of these indicators creates a framework linking availability of climate resources to energy production, hydraulic production and efficiency. The comparison of the two models in Karbala and Mosul can be defined in respective metrics oriented to productivity and efficiency which can fairly capture agricultural results and technical system behaviour.

3.4 Climatic data and processing

To define the climate boundary conditions influencing the functioning of the system at each site, the daily climatic and solar radiation measures were retrieved from NASA Prediction of Worldwide Energy Resources (NASA POWER) database, at the geo-coordinates of Mosul (province of Nineveh) and at Karbala site. Following the procedures outlined in UNFCCC's IPCC and COMPLETED, the chosen data source is extensively used in the fields of photovoltaic and agricultural energy, among others, due to its global scale, long-term consistency, and verified reanalysis-based datasets from MERRA-2 and CERES product.

The climatic variables were the air temperature extremes near the surface (T2M_MAX and T2M_MIN), relative humidity at 2 m height (RH2M), corrected precipitation (PRECTOTCORR) and indicators of solar radiation. The shortwave downward irradiance (TOA_SW_DWN) at the top-of-atmosphere (TOA) from CERES SYN1deg, measured in MJ/m^2/day and converted to kWh/m^2/day, was used for solar resource assessment. The climatic specifications sheet used in the research summarizes the definitions and physical meanings of these variables.

Data on climate from daily sources were downloaded for the winter (December 2025–January 2026). The dataset utilized a daily temporal resolution that was consistent with the study used seasonal-scale analysis. Whenever screening for missing records, outliers, and physically inconsistent values is necessary and observed, the QC procedures are applied. In the case of any minor gaps, validation was done using trends from the previous day. The average monthly and seasonal values were computed using verified data sets.

The climatic datum collected by processing is aggregated to get descriptive statistics and comparative indicators for these two locations. The indicators were used to interpret observed differences in photovoltaic energy production, effective operating hours and water delivery performance. The daily time-series were also useful for generating plots to compare the variability of solar irradiance, temperature and precipitation as supportive evidence to his field-based analysis of system productivity.

The average climatic parameters for the two sites during the winter monitoring period are given in Table 2. Karbala, compared to Mosul, showed continuously higher solar irradiance, higher minimum and maximum temperatures, lower relative humidity, and significantly lower precipitation, results show. COP26 has come to an end and the World is to plan on restructuring the planet so that it will minimize the green-house effect.

Table 2. The average climate of Mosul (Nineveh) and Karbala (Dec 2025–Jan 2026).

Climatic Parameter	**Mosul (Nineveh)**	**Karbala Governorate**
Average Solar Irradiance (kWh/m²/day) (TOA_SW_DWN)	16.51	18.98
Average Maximum Temperature (°C) (T2M_MAX)	12.49	17.11
Average Minimum Temperature (°C) (T2M_MIN)	3.02	6.72
Average Relative Humidity (%) (RH2M)	66.69	52.12
Average Daily Precipitation (mm/day) (PRECTOTCORR)	2.40	0.59

4. Results

4.1 Field Performance Results – Mosul (Nineveh Governorate)

A solar-powered irrigation system was stationed at the Al-Hamdaniya Agricultural Extension Farm (Mosul). The system performed stably in the monitoring period for winter (November–January) under the wheat irrigation. The system was effectively operational around midday, with a peak discharge recorded between 11:00 and 13:00. Water volume delivered on a daily basis ranged from 306 m³/day (minimum, December) to 417 m³/day (maximum, November), with an average of 366 m³/day during winter. The results show that the northern site can operate successfully in winter in the solar window.

4.2 Field Performance Results – Karbala Governorate

At the Desert Agricultural Extension Farm (Karbala), the similarly designed solar water pumping system yielding more winter field output under identical irrigation schedule. The hourly discharge pattern shows a longer operating range compared to Mosul, where pumping commences earlier in the morning and continues later in the afternoon. The peak discharge in a particular hour of the day was observed between 82 m³/h 93 m³/h. Water output in the winter months ranges from about 382 m³/day in December (minimum) to about 460 m³/day in January (maximum), having an overall average of about 410 m³/day. This result means that more effective energy is available for WUE (biomass) production at the winter, arid southern site.

4.3 Comparative Results Between the Two Sites

The comparison of the winter field performance showed that Karbala produced more water than Mosul, with both systems having the same specifications and operational practices. According to Table 3, the average water production at Karbala (410 m³/day) is about 10–15% more than that at Mosul (366 m³/day). The monitored difference matches with the noted higher daily solar irradiance at Karbala during the observation period. Figure 1 shows the observed solar irradiance comparison while the functionality reflects longer effective pumping hours and higher volumes delivered.

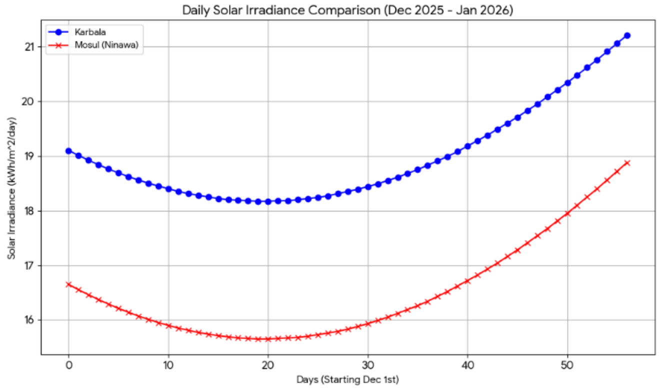

Figure 1. Comparison of daily solar irradiation (kWh/m²/day) between Mosul (Nineveh) and Karbala throughout winter monitoring period (Dec 2025–Jan 2026).

According to Figure 1, irradiance in Karbala was consistently higher than that of Mosul. In other words, the boost in irradiance assists in further expanding the effective operating window and supports the increased water production in the winter season, while both systems are designed identically.

The variation in performance is mainly due to the site climatic conditions that have higher solar irradiance levels and longer effective working hours in Karbala location. The results indicate that the installation location has a decisive role in the actual performance of solar-powered irrigation systems, with the irrigation scheduling and system design being equal. Additionally, Table 3 reveals that the Karbala system was able to operate at extended hours, with pumping starting early in the morning and ending late in the afternoon. The increase in delivered water volume directly resulted from the wider operational window. On the other hand, the Mosul system had a more peak operational time around midday which decreased energy use daily and total water production.

Table 3: Results of Comparative Field Performance (Winter Season)

Performance Indicator	Mosul (Nineveh)	Karbala	Difference / Enhancement
Average daily water output (m³/day)	366	410	+44 m³/day (≈12.0% higher)
Maximum daily output (m³/day)	417 (Nov)	460 (Jan)	+43 m³/day (≈10.3% higher)
Minimum daily output (m³/day)	306 (Dec)	382 (Dec)	+76 m³/day (≈24.8% higher)
Peak discharge window (h)	11:00–13:00	11:00–13:00	Similar peak window; longer tails in Karbala
Effective operating pattern	Midday concentration	Extended morning/afternoon	Longer effective duration in Karbala

This hourly comparison confirms the findings from Table 3 and Figure 2 regarding diurnal and seasonal performance advantage at Karbala. More significantly, the performance advantage is not just a higher peak output, but a longer effective pumping duration. As a result, the southern site shows an increase in winter water production, due to both peak capacity and operating time.

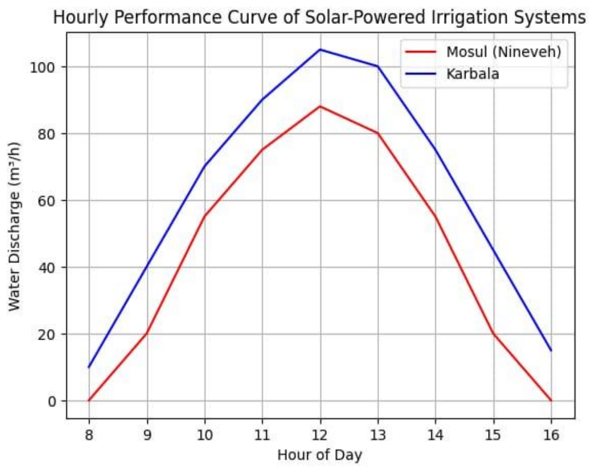

Fig 2. Curves that Show Solar Irrigation System Performance Per Hour.

The hourly performance curves for the Mosul (red curve) and Karbala (blue curve) solar-powered irrigation systems are shown in Figure 2. It can be observed in the figure that the Karbala site has a significantly higher operating time and midday discharge than the Mosul site despite them being the same systems.

5 . Discussion

5.1 Effect of Climatic Location on System Performance

Climate locations are shown to determine the operational performance of solar-powered irrigation technology. Although the system, pump specifications and irrigation schedule for the wheat crop are the same at both sites, the Karbala site achieved consistently higher energy availability, effective operating hours and water delivery than the Mosul site. This indicates that under real agricultural operation, it is the environmental and climatic boundary conditions that dominate the productivity of photovoltaic pumping. The underperformance mainly arose because the southern desert site has higher solar irradiation and longer sunshine duration than the central and northern sites. As illustrated in the results section, these conditions not only augmented the photovoltaic energy generation and the daily operating window but also increased the water discharge and the system utilization. Earlier studies note that performance of solar pumps in arid regions is largely governed by intensity of irradiance and length of day.

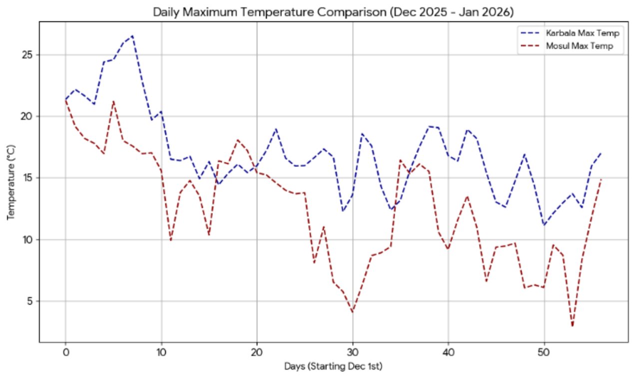

Fig 3. A comparison of daily maximum temperatures in the winter monitoring period for Mosul and Karbala.

Along with solar radiation, ambient temperature also affects the system performance, impacting the photovoltaic conversion efficiency as well as the operation of motor–pump. The daily maximum temperature outputs of the two sites during the monitoring period were shown in Figure 4. The Karbala site typically experienced higher temperatures levels typical of the desert. While a higher temperature may reduce the efficiency of a PV module, in this study, this effect seems to be lesser than the effect of solar irradiance. This shows that in winter operating conditions, the solar resource gain exceeds losses occurring due to temperature.
Table 4 also reinforces this view by providing the average climatic parameters for both locations. The intense solar irradiance, greater minimum and maximum temperatures, as well as the lower relative humidity in Karbala, confirm the desert climatic regime. The lower levels of humidity and less cloud formation in the south make solar radiation more available, making the system operation more stable. On the contrary, ascribed to

greater attenuation of solar radiation northern site was high humid low temperature area.

Table 4: The climatic conditions at Mosul and Karbala (Dec–Jan)

Climatic Parameter	Mosul (Nineveh)	Karbala Governorate
Average Solar Irradiance (*kWh/ m^2 / day*)	16,51	18,98
Average Maximum Temperature (C°)	12,49	17,11
Average Minimum Temperature (C°)	3,02	6,72
Average Relative Humidity (%)	66,69	52,12
Average Daily Precipitation (*mm/day*)	2,40	0,59

According to Rainfall variation diagram (Figure 5) during the monitoring period, the magnitude and occurrence of Mosul rains event was greater than that of Karbala.The operational implications of such variability are important. The rising precipitation in Mosul can sometimes lessen irrigation demand and limit daily pumping duration. Cloudy and rainy weather also diminishes solar radiation and reduces the operational window. On the contrary, the more limited the water in Karbala is, the more supported are the irrigations and the daily working situation. Thus, the combined impacts of solar irradiance and temperature, humidity and rainfall variabilities explain the greater winter productivity at the southern site.

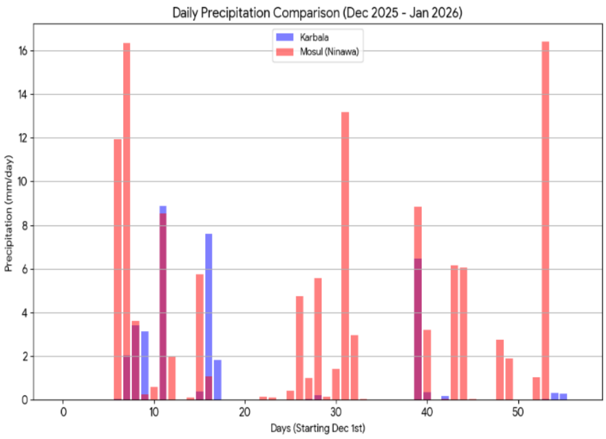

Fig 4. Comparison of the Rain in Mosul (Nineveh) and Karbala (2025-2026)

The selection of sites and climate suitable for solarisation of irrigation system is essential for deployment of solar energy irrigation systems. The efficiency of seasonal water delivery and of the distribution system depends, inter alia, on climatic conditions of the region in which it is located, even when the design, capacity and working of the system are standardised. As such, future solar irrigation projects in Iraq and similar semi-arid regions should incorporate a detailed investigation of climate conditions during the planning stage to enhance performance and water–energy productivity.

5.2 Role of solar radiation incidence and tilt angle

The tilt angle of the photovoltaic panel for both locations was prepared following a geographical latitude adjustment that contributed to improving solar radiation capture and reducing reflection losses. As a result, the incidence of solar throughout the studying time was nearly optimal and the system was stable during winter. Although both regions are applying similar design criteria, despite northern and southern Iraq's inherent difference in the path and intensity of the solar radiation, was not equal.

The southern desert environment of Karbala was more advantageous in winter solar geometry, having a higher effective solar elevation and longer daily irradiation window. Due to these conditions, the duration of photovoltaic operation and energy production increased. Conversely, the Mosul northern site suffers from low solar elevation angles, short sunshine duration, and severe atmospheric attenuation from cloud and humidity. As such, the panel tilt optimization exerted a greater influence at the southern site due to the reason that a better solar incidence increased the productivity of the system. The outcomes show that optimizing tilt angles won't mitigate regional climate change. The functioning of the system depends not only on one factor but on the solar geometry, atmospheric condition and seasonal irradiance distribution. The system size and performance prediction models must incorporate regional solar resource characteristics, especially for winter irrigation in semi-arid and arid regions.

5.3 Iraq's Application of Solar-Powered Irrigation Systems

As the findings suggest, location suitability on climate criteria could usefully be employed for the planning and deployment of solar-powered irrigation in Iraq. When designs are standardized, they become easier to implement and economical. However, the current findings reveal that similar technologies can yield varied field results due to differences in climate. The variations directly affect the supply of water, agricultural production and the long-run economic sustainability.

In areas such as Karbala and other central-southern governorates located in the desert and arid region, further increased solar irradiance and sunshine duration is likely to be a great asset for solar irrigation, especially in the winter when irrigation demand is high and alternatives may fail. Implementing solar irrigation in all regions potentially enhances water-energy efficiency and climate resilience at scale. In humid northern regions, in order to optimize performance on advanced system design designs, energy storage, hybridization with other sources and irrigation scheduling process which is flexible and takes seasonal changes. The discrepancies in productivity may lessen, and the system may exhibit improved reliability under adverse weather conditions.

To sum up the paper, the assessment of climatic resources needs to be included in the framework for national planning of solar irrigation development activities in Iraq. To ensure the optimal selection, long-term sustainability, and water–energy productivity's maximization, future initiatives should be formulated based on an exhaustive solar resource mapping, climatic risk analysis, and performance modeling of diverse PV systems.

6. CONCLUSIONS

An integrated field–numerical assessment of a couple of similar solar-powered irrigation systems has been developed in two different climatic conditions in the north (Mosul) and the central–south (Karbala) desert regions of Iraq. Based on the study results, climatic location impacts the actual field performance and productivity of photovoltaic irrigation systems widely.

Observations in the filed in winter showed that the same water output and effective hours were better in the case of the system of Karbala compared to the Mosul system notwithstanding the same specification and irrigation programming. Daily water production at Karbala was higher than Mosul by about 10–15% mainly due to higher solar irradiance and longer sunshine hours. Analysis of the hourly performance further confirmed this difference with a wider operating range and higher peak discharge at the southern site.

As per climatic analysis, solar irradiance, temperature regime, humidity and variability of rainfall also jointly contributed in difference performance. The dry desert conditions of Karbala provided favorable operating conditions for IME, such as higher radiation availability and less atmospheric attenuation. In contrast, the northern site received more rainfall and variability in weather, allowing for better solar gain and less pumping time.

Results further showed that tilt-angle optimization as a function of latitude induced better solar radiation incidence at both sites. However, further design measures could not reduce differences due to regional climate. In this regard, the effectiveness and reliability of solar irrigation systems depend largely on correct site selection and climatic assessment.

The findings illustrate the importance of assessing climatic resources in planning solar irrigation projects as well as their deployment in Iraq from a practical point of view. The dry and semi-dry areas can be used for large-scale deployment. The northern regions may require a hybrid solution or a change in operational practices to improve performance. In conclusion, this study provides field evidence that the performance of solar irrigation depends on environmental characteristics despite having the same system design. In Iraq and similarly affected states, the future research should focus on long-term monitoring, seasonal variation, effects of dust accumulation and techno-economic analysis for better water-energy management towards sustainable agriculture.

References

[1] Food and Agriculture Organization of the United Nations (FAO), German Agency for International Cooperation (GIZ). International Workshop: Prospects for solar-powered irrigation systems (SPIS) in developing countries. Final report. Rome, Italy; 27–29 May 2015.

[2] M. Salman, A. Abdelfattah, W. Ahmad, C. Simongini. The use of solar energy in irrigated agriculture: a sourcebook for irrigation water management with alternative energy solutions. Rome: FAO; 2022. https://doi.org/10.4060/cb8459en .

[3] O. V. Shepovalov, A. T. Belenov, S. V. Chirkov. Review of photovoltaic water pumping system research. Energy Reports. 2020; 6:306–324. https://doi.org/10.1016/j.egyr.2020.08.053 .

[4] N. M. Ahmed, A. M. Hassan, M. A. Kassem, A. M. Hegazi, Y. F. Elsaadawi, et al. Reliability and performance evaluation of a solar PV-powered underground water pumping system. Scientific Reports. 2023; 13:14174. https://doi.org/10.1038/s41598-023-41272-5 .

[5] M. Jraidi, A. Cherif. Effects of temperature and solar irradiation variations on the performances of photovoltaic pumping systems. New Energy Exploitation and Application. 2024;3(1). https://doi.org/10.54963/neea.v3i1.244 .

[6] M. H. Salman, A. A. Obed, A. J. Abid. Performance study of the direct-coupled photovoltaic water pumping system for the rural-isolated agricultural region in Iraq. *Journal of Techniques*. 2021;3(1):37–46. https://doi.org/10.51173/jt.v3i1.273 .

[7] L. Gevorkov, J. L. Domínguez-García, L. T. Romero. Review on Solar Photovoltaic-Powered Pumping Systems. Energies. 2023;16(1):94. https://doi.org/10.3390/en16010094

[8] A. A. Kazem, M. T. Chaichan, H. A. Kazem. Dust effect on photovoltaic utilization in Iraq: Review article. Renewable and Sustainable Energy Reviews. 2014; 37:734–749. https://doi.org/10.1016/j.rser.2014.05.073 .

[9] M. Tawalbeh, A. Al-Othman, F. Karfiah, M. Alkasrawi. Environmental impacts of solar photovoltaic systems: A critical review of recent progress and future outlook. Science of the Total Environment. 2021; 759:143528. https://doi.org/10.1016/j.scitotenv.2020.143528 .

[10] H. Abuzaid, et al. Impact of dust accumulation on photovoltaic panels: a review. *Journal of Environmental Science and Health, Part A. 2022.* https://doi.org/10.1080/19397038.2022.2140222 .

[11] A. Al-Karaghouli, L. L. Kazmerski, Renewable energy opportunities in Iraq: A review, Renewable and Sustainable Energy Reviews, 2019, 98, 313–330. http://dx.doi.org/10.1016/j.rser.2008.05.007 . Supports climatic and solar variability in Iraq.

[12] World Bank, Solar irrigation and groundwater management: Opportunities and risks in developing countries, 2020. https://doi.org/10.1596/33915 . Supports regional irrigation and solar context.

[13] NASA Surface Meteorology and Solar Energy database (SSE). Supports irradiance differences.

[14] D. H. Muhsen, T. Khatib, F. Nagi. A review of photovoltaic water pumping system designing methods, control strategies and field performance. Renewable and Sustainable Energy Reviews. 2017;68(P1):70–86. https://doi.org/10.1016/j.rser.2016.09.129 .

[15] R. Rawat, S. Kaushik, R. Lamba. A review on modeling, design methodology and size optimization of photovoltaic based water pumping, standalone and grid connected system. Renewable and Sustainable Energy Reviews. 2016;57:1506–1519. https://doi.org/10.1016/j.rser.2015.12.228

[16] A. Mokeddem, A. Midoun, D. Kadri, S. Hiadsi, I. Raja. Performance of a directly-coupled PV water pumping system. Energy Conversion and Management. 2011;52(10):3089–3095. https://doi.org/10.1016/j.enconman.2011.04.024 .

[17] S. Renu, P. Onaygil. Energy performance of PV-powered water pumping systems: A case study. Solar Energy. 2017;155:1326–1338. https://doi.org/10.1016/j.solener.2017.07.058

[18] M. N. I. Sarkar, H. R. Ghosh. Techno-economic analysis and challenges of solar powered pumps dissemination in Bangladesh. Sustainable Energy Technologies and Assessments. 2017;20:33–46. https://doi.org/10.1016/j.seta.2017.02.013

[19] A. N. Tchudjo-Tchuente, J. Ouamba-Fedjo, A. Fopah-Lele, J. G. Tamba. Evaluating the Levelized Cost of Energy (LCOE) of irrigation systems based on solar PV and diesel generator for a green bean crop in Cameroon. Energy Strategy Reviews. 2025;61:101826. https://doi.org/10.1016/j.esr.2025.101826

[20] S. Mallappa, K. K. Bansal. Economic feasibility and farmer adoption of solar irrigation pumps: Evidence and implications. Energy Strategy Reviews. 2026;64:102094. https://doi.org/10.1016/j.esr.2026.102094

[21] E. Skoplaki, J. A. Palyvos. On the temperature dependence of photovoltaic module electrical performance: A review of efficiency/power correlations. Solar Energy. 2009;83(5):614–624. https://doi.org/10.1016/j.solener.2008.10.008

[22] E. Skoplaki, J. A. Palyvos. Operating temperature of photovoltaic modules: A survey of pertinent correlations. Renewable Energy. 2009;34(1):23–29. https://doi.org/10.1016/j.renene.2008.04.009

[23] R. Gelaro, W. McCarty, M. J. Suarez, et al. The Modern-Era Retrospective analysis for Research and Applications, Version 2 (MERRA-2). Journal of Climate. 2017;30(14):5419–5454. https://doi.org/10.1175/JCLI-D-16-0758.1

[24] A. D. Quansah, F. Dogbey, P. J. Asilevi, et al. Assessment of solar radiation resource from the NASA-POWER reanalysis products for tropical climates in Ghana towards clean energy application. Scientific Reports. 2022;12:10684. https://doi.org/10.1038/s41598-022-14126-9

[25] S. Sayago, G. Ovando, J. Almorox, M. Bocco. Daily solar radiation from NASA-POWER product: Assessing its accuracy considering atmospheric transparency. International Journal of Remote Sensing. 2020;41(3):897–910. https://doi.org/10.1080/01431161.2019.1650986

[26] International Renewable Energy Agency (IRENA). Solar pumping for irrigation: Improving livelihoods and sustainability. Abu Dhabi; 2016. ISBN 978-92-95111-94-3