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Research Article

Experimental Analysis of Weather Condition Effects on Photovoltaic Systems' Performance: A Jordan Case Study

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Energy generation and economic development are closely linked, with energy playing a pivotal role in wealth creation. However, the finite nature of fossil fuel resources and associated environmental challenges has emphasized the need for sustainable energy alternatives based on renewable sources. Among these alternatives, photovoltaic (PV) systems hold significant potential for fostering a sustainable energy system. Despite ongoing material research, achieving a major breakthrough in enhancing the conversion efficiency of commercial PV modules remains a challenge. To optimize PV system yield, installation must consider geographic location and design factors. PV modules often yield different results compared to manufacturer specifications due to factors such as high temperatures, dust, and arid to semiarid climates. Therefore, it is crucial to conduct outdoor testing and characterization of PV modules tailored to specific locations, such as Jordan, to maximize system performance. This research aims to examine the impact of ambient temperature, dust accumulation, and solar irradiance intensity on PV system performance in Jordan, providing valuable insights through monitoring power output variations. The findings will contribute to improving PV system efficiency in Jordan's unique climate and aid manufacturers in developing innovative PV applications. The collected data includes solar radiation, temperature, voltage, current, and output power. The results confirm that the Azraq site is a better location when compared to Mafraq based on the possibility of generated more output power using a PV system.

Keywords: climatic factors; environmental factors; PV systems; solar location evaluation; weather station

1. Introduction

Since 2011, it has been observed that the world energy demand growth rate is about 1.8% per year. This continuous growth deteriorates the Earth's ecological system and causes global warming phenomena as well as a rise in the CO2 emission rate. The factors mentioned above motivate researchers to find alternative sources for conventional energy, in which the environmental aspect is taken into consideration [1–5].

Renewable energy sources such as solar, wind, hydroelectric, and bio are becoming popular options for meeting the rise in energy demands [6–8]. Governments around the globe are urging policy reforms to promote renewable energy deployment. Thus, by 2022, the capacity of renewable energy sources installed worldwide is more than double that of 2011. Solar energy is the most viable option among renewable energy sources especially in Jordan. During 2023, 29% of electricity generated in Jordan was by renewable energy resources [9–12]. Photovoltaic (PV) systems could be implemented and used with a low system cost, as a result of the steady increase in electricity prices; in addition, a noticeable drop in the cost of PV systems means that they could compete with electricity prices both nationally and regionally in locations with high irradiation, such as the solar belt regions, like Jordan [13, 14]. The performance of PV panels in dry arid and semiarid environments like our study areas is influenced by the ability of the glass cover to transmit solar radiation into the absorber and the ambient air temperature. The dust in the ambient air carried by the wind can accumulate on the solar PV devices external surface and obscure the solar radiation and, therefore, reduce PV panels' performance [15].

In the pursuit of sustainable energy solutions, PV systems have emerged as a promising strategy to address the escalating global energy demand while mitigating environmental consequences [16, 17]. This work was a research project funded by the Scientific Research Deanship at Al-al-Bayt University/Jordan. Jordan imports most of its energy needs from outside, so Jordan's government decided to diversify energy resources in the energy mix. Therefore, many renewable energy projects, especially PV solar energy projects, have been established in the last 10 years everywhere in Jordan, as Jordan is one of the best countries in the Middle East and North Africa (MENA) region regarding solar energy resources. The main idea beyond this work is to find a method that can be used here in Jordan or in any area similar to how to choose the best area for PV solar energy systems, taking into account the most important parameters that affect the performance of PV systems. The Hashemite Kingdom of Jordan, situated in a region abundant with solar radiation, has acknowledged the pivotal role of harnessing solar energy as a foundational element of its renewable energy strategy [18]. Within this context, the comparative analysis of various locations within the kingdom assumes a pivotal role in optimizing PV energy production and facilitating well-informed decision-making [18].

This analysis centers on two focal cities: Azraq and Mafraq, each marked by distinct attributes that shape their potential for PV energy production. Azraq, situated in Jordan's eastern desert region, benefits from exceptional geographical and climatic conditions that augment its solar energy potential [19, 20]. Conversely, Mafraq, situated in the northern desert region, presents its own array of environmental dynamics that influence its suitability for PV energy generation [19–21]. A comprehensive comparison of PV energy production at these two sites holds the promise of yielding valuable insights critical to shaping optimized energy strategies [22]. These insights encompass variations in solar radiation, temperature profiles, dust accumulation, and other factors that directly impact the efficiency of PV systems in these contexts [6, 23]. Through a comprehensive analysis of this dataset, decisions pertaining to system design, panel orientation, cleaning protocols, and other essential considerations can be guided, ultimately maximizing energy output while ensuring the sustained viability of the PV installations [24, 25].

This study seeks to unravel the intricate interplay between geographic, climatic, and environmental elements and their consequential effects on PV energy production [24]. Leveraging the unique attributes of Azraq and Mafraq, the study aims to deepen the understanding of the potential challenges and opportunities associated with differing site conditions. As Jordan steadfastly pursues sustainable energy, this comparative analysis holds the potential to design PV energy systems that are more efficient, robust, and adaptable to the specific requirements of each locale [26].

Jordan confronts a formidable energy landscape characterized by escalating consumption, dwindling traditional energy resources, and environmental considerations [27]. To address these challenges, Jordan has unveiled an ambitious renewable energy strategy, with a central emphasis on harnessing its abundant solar resources [28]. In this context, Azraq and Mafraq, two strategically significant cities within Jordan, have drawn attention due to their unique attributes that can significantly influence their capacity for PV energy generation [29].

Azraq's distinctive geological and geographical features make it a captivating case for PV energy production. Its geological formations and climatic conditions establish a unique context that can either amplify or impede the performance of PV systems [30]. In contrast, Mafraq, with its diverse topography and fluctuating solar radiation patterns, introduces additional complexity to the PV equation. Through a comprehensive analysis of these two sites, our aim is to uncover the intricate interplay of factors such as solar radiation, climatic conditions, geographical location, and topographical features that collectively shape the energy generation potential of each location [31].

The implications of this comparative study extend significantly to energy planners, policymakers, and researchers alike. By evaluating the PV energy production capabilities of Azraq and Mafraq, our objective is to contribute to the decision-making process that steers Jordan's renewable energy trajectory [32]. Through a meticulous examination of these two sites, we underscore the significance of recognizing the site-specific nuances that optimize solar energy generation. In doing so, we bring the kingdom closer to the realization of its sustainable energy ambitions [32].

As the global shift towards sustainable energy solutions progresses, PV systems have taken center stage in the quest for clean power generation [22]. As nations endeavor to diversify their energy portfolios and mitigate the ecological impact of conventional energy sources, the utilization of solar energy through PV systems presents substantial potential [21]. The Hashemite Kingdom of Jordan, recognizing the pivotal importance of transitioning to renewable energy sources, has positioned itself as a notable participant in this worldwide movement. This assessment not only holds implications for optimizing energy generation in these specific locations but also for propelling Jordan's broader goals of ensuring energy security and sustainability [18].

The present work aims to clarify the effect of solar radiation, dust deposition, and ambient air temperature on PV panel energy output in two different sites in Jordan. In addition, this study will provide a recommendation for PV system designers, policymaking, people who work in the energy sector, and investors regarding which areas are suitable for PV solar energy system deployment in Jordan. These aims will be achieved by a methodology designed for this work [33, 34]. This paper is organized as follows. Section 1 contains introduction. Section 2 contains the background. Section 3 contains the methodology. Section 4 contains collected measurements. Section 5 contains results and discussion. Finally, the conclusion of the research is drawn in Section 6.

2. Background

Jordan's geographical location has a substantial impact on its potential for harnessing renewable energy, particularly solar energy. Positioned at the heart of the Middle East, Jordan benefits from its strategic placement in a region abundant in solar irradiance [35]. Its approximate coordinates, ranging between latitude 29.1832°N and 33.3756°N and longitude 34.9822°E and 39.3010°E, ensure ample exposure to sunlight throughout the year, further enhancing its solar energy potential [36]. Being situated within the Sun Belt, characterized by high solar radiation, bolsters its solar energy viability [21]. The Jordanian government's recognition of this geographical advantage is evident in its prioritization of solar energy as a central component of the nation's renewable energy strategy [18]. This strategic location, coupled with a commitment to sustainable development, positions Jordan as a promising contender in the global transition to clean and renewable energy sources.

Azraq, located in eastern Jordan, stands out with its arid desert landscape featuring extensive sand dunes and rugged terrain, as shown in Figure 1 [35]. The flat topography of the region facilitates unhindered sunlight exposure, a vital advantage for efficient solar energy generation [36]. This geographical attribute allows for optimal positioning of solar panels, enabling effective capture of solar energy and potentially enhancing PV energy production.

In contrast, Mafraq, situated in the northern part of Jordan, boasts a diverse landscape that encompasses rolling hills, fertile plains, and urban infrastructure, as shown in Figure 1 [26]. The undulating terrain introduces variables that could impact sunlight distribution and solar panel orientation [36]. The hilly landscape of Mafraq presents unique challenges and opportunities for the effectiveness of PV systems, requiring meticulous panel placement to optimize energy capture.

The solar radiation profiles of both Azraq and Mafraq play a pivotal role in their suitability for solar energy generation. Azraq, situated in a desert environment, benefits from abundant solar radiation year round, making it an ideal location for efficient solar energy utilization [21]. Similarly, Mafraq experiences substantial solar radiation, although potential variations may arise due to geographic disparities and local weather patterns [19]. The favorable solar radiation levels in both cities establish promising conditions for successful PV energy production.

Climate significantly influences the feasibility of solar energy systems. Azraq's desert climate, characterized by hot summers and relatively mild winters, leads to daily temperature fluctuations that impact the operational efficiency of solar panels [37]. In contrast, Mafraq's semiarid climate features hot and dry summers, coupled with cooler winters, introducing distinctive challenges and opportunities for PV system performance [19].

Topographical characteristics further mold the solar energy potential of Azraq and Mafraq. Azraq's predominantly flat terrain, intermingled with sporadic sand dunes and rocky formations, facilitates unobstructed sunlight exposure for solar panels [21]. This lack of significant geographical features maximizes the efficient utilization of available sunlight. Conversely, Mafraq's varied topology, comprising hills and plains, may require strategic panel orientation to optimize energy capture [37].

Figure 1: Map of Jordan's urban centers and cities [18].

Altitude and geographical location further contribute to the distinct energy profiles of Azraq and Mafraq. Azraq's low altitude, characteristic of desert regions, aligns with its location in the eastern desert area [20]. In contrast, Mafraq's higher altitude, resulting from its northern geographical placement, influences local weather patterns and temperature fluctuations [26]. According to the findings of [38], the efficiency of PV modules experiences a decline of 3%-4% when subjected to high temperatures ranging from 50°C–60°C (50°C–60°C) [39]. The study also highlights the impact of elevated ambient temperatures on the power output at the site.

The study will be conducted at Al Al-Bayt University campus/Al-Mafraq and Al-Azraq, both of which are primarily characterized as semiarid climates with moderate temperatures and distinct seasonal variations. Figure 2 reveals that the average annual temperature during winter ranges from 8°C to 10°C, while summer temperatures range from 28°C to 35°C. The rainy season occurs between November and April, with average annual rainfall varying from less than 150 mm to over 200 mm in certain seasons. These areas have been selected as the study sites for the PV field test in Jordan for several reasons. First, they possess the highest solar radiation levels in Jordan. Second, they offer ample space for PV system projects, with most proposed projects already implemented in these areas. Lastly, the two sites are geographically distinct within Jordan. Figure 3 shows the solar radiation distribution levels for the entire country [40].

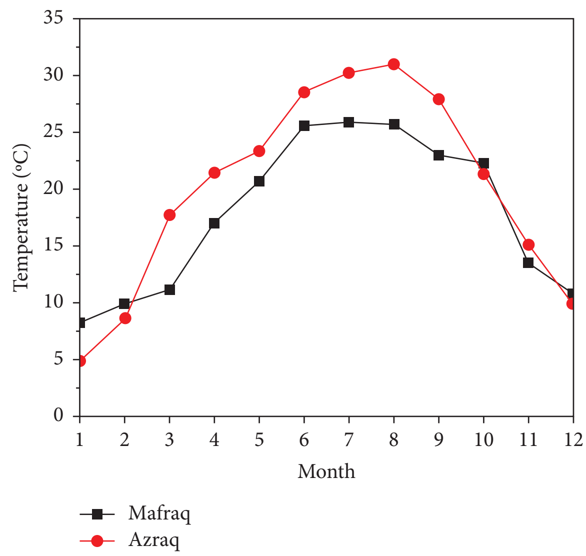

Figure 2: Mean ambient temperature °C.

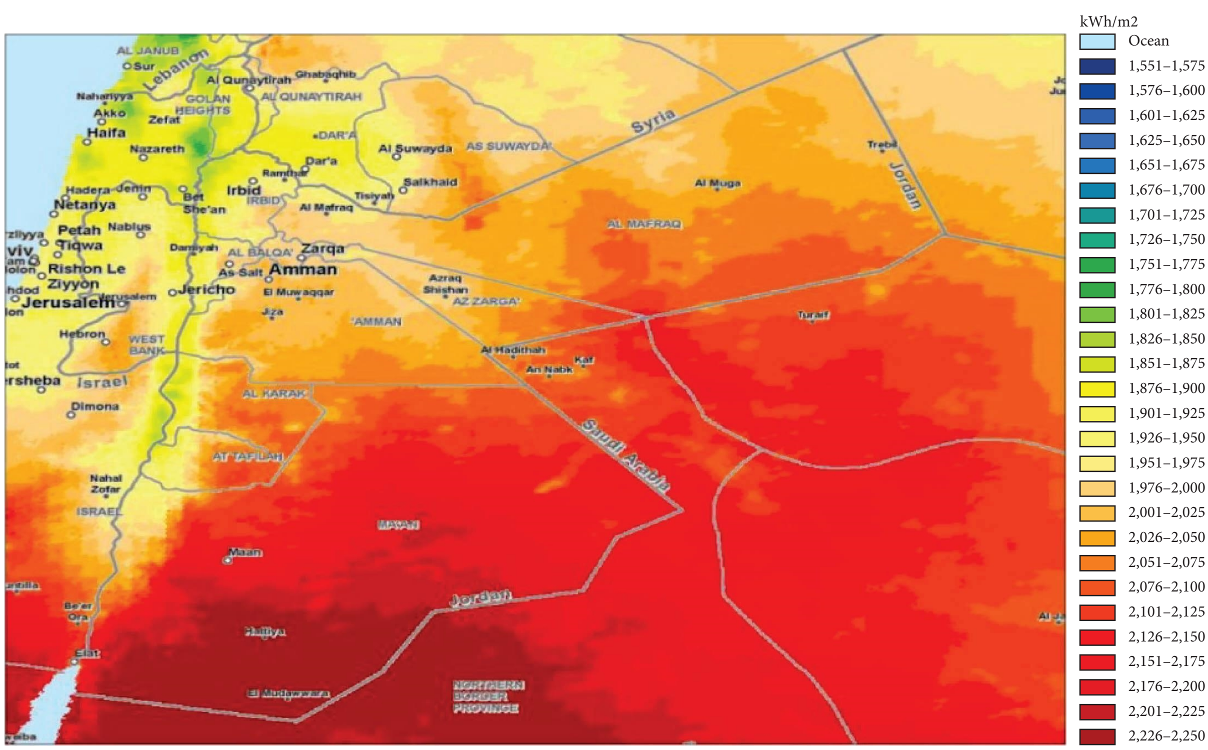

Figure 3: Jordan solar radiation levels [40].

3. Methodology

The methodology of this study will be a Jordan PV network of the national scientific and commercial PV community composed based on different steps as shown in Figure 4.

4. Collected Measurements

Two identical weather stations, Figure 5, have been installed in two different areas (Mafraq and Azraq). Mafraq is located in northeast of Jordan and can be considered as semiarid region, while Azraq is located in desert area in east of Jordan and can be considered as arid region. Mafraq has good level of solar radiation, high temperature in summer, and moderate dust storms, while Azraq region has high level of solar radiation, high temperature in summer, and high level of dust storms. Most of the MW PV projects in Jordan have been installed in three areas (Mafraq, Azraq, and Maan). Maan is located in the south of Jordan and it be considered one of the best locations in country for solar energy projects.

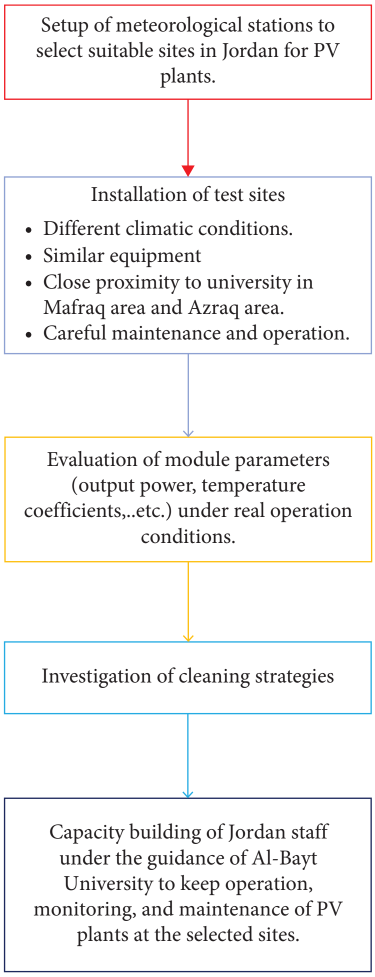

Figure 4: The methodology steps of this study.

Figure 5: Weather station setup.

Weather station has many components to measure many parameters. One of the main components is the PV module. Two modules have been used in each weather station (250 W) each, with 500 W peak total of each station. The characteristics of module shown in Figure 6.

The assembly in the outdoor atmosphere at two sites consists of two polycrystalline PV modules mounted on a south-facing metal stand with a fixed tilt angle utilized in this study. The amount of PV power output due to environmental effects was calculated from the measured electrical parameters of each site. The pyranometer is oriented at an angle to the PV modules to measure global solar radiation. The experimental measurements are carried out on the roof of the two sites. The measured parameters are the maximum current, the maximum voltage, the output power, the weather parameters, solar radiation, wind speed, humidity, and the panel's surface temperature of both sites collected. The voltage and current of each module are measured using two digital multimeters. The temperature is recorded using a digital IR thermometer. After collecting all the data, maximum power is calculated through maximum voltage and maximum current using the following formula:

$$P_{\max} = I_{\max} \times V_{\max}, \quad (1)$$

where the $P_{\max}$ is the maximum output power of the PV module, the $I_{\max}$ is the maximum output current of the PV module, and the $V_{\max}$ is the maximum voltage of the PV module.

Weather stations have been installed in Mafraq and Azraq at the end of 2016 year. Weather stations have been started to collect data for 1 year at first of January 2017 until 31/12/2017. Data have been collected minute by minute during 1 year. Parameters that have been collected are solar radiation, wind speed, wind direction, temperature, pressure, relative humidity, voltage and current. More than 525,600 data have been collected for each parameter. The effect of three important parameters on power output have been considered, which are, solar radiation, temperature and dust [41–46]. Regarding solar radiation and temperature, 525,600 min by minute data have been collected, while for dust, the PV modules in the two locations will not be cleaned for the whole year.

5. Results and Discussion

The results of two PV modules in two sites in Jordan, for an average value of 1 year, are presented to study the solar radiation, temperature and dust impacts on the efficiency of the PV system and to determine how these affect the power output. The radiation and temperature were measured for 1 year to calculate the average solar energy (KWh/m^2/day) over the months of the 2017 year in two sites in Jordan. The data were measured using one weather station in each site and data was logged at 1-min intervals. The Figure shows high solar irradiance for the specified locations, especially in the summer months.

Figure 6: Photovoltaic module specification.

Table 1: Comparison of average daily solar radiation and mean ambient temperature data.

Readings	Al-Mafraq location readings		Al-Azraq location readings	
Month	Irradiation (Wh/m^2. day)	Temperature (°C)	Irradiation (Wh/m^2. day)	Temperature (°C)
January	3617	8.3	3710	4.9
February	4052	9.9	4132	8.6
March	5492	11.2	5740	17.7
April	6921	17.0	7122	21.4
May	7669	20.7	7556	23.3
June	8303	25.6	8324	28.5
July	8222	25.9	7786	30.2
August	7625	25.7	7458	31.0
September	6535	23.0	6583	27.9
October	4937	22.3	5112	21.3
November	3736	13.5	3524	15.1
December	2921	10.8	3245	9.9
Yearly average	5836	17.8	5784	20.0

Table 1 shows the monthly average variation of ambient temperature (°C) and monthly average solar radiation (Wh/m^2.day) for the year 2017 in two sites. From this pattern of variation, it is seen that the ambient temperature and solar radiation vary with the different months of the year throughout the study. It is noticed that the PV module in Azraq captures more solar irradiance than the one in Mafraq. The performance of a PV module is mainly affected by dust accumulating on its surface. A PV module's output also depends on the module's temperature. A PV module is rated at 25°C, but when operating in the field, they generally operate at higher temperatures. PV modules in Azraq show a more significant temperature rise as compared to those in Mafraq. This may be due to the high rate of dust accumulation or because the temperature in Azraq is generally higher.

Figure 7 shows the average daily solar radiation incident on one square meter area (kWh/m^2.day). As shown from the figure, the monthly average daily solar radiation incident on square meter area in Azraq area is more than for Mafraq area during winter and spring months (December, January, February, March, and April). The reason for that is the cloudy cover is more for Mafraq than for Azraq area in winter and spring months, where Azraq is located in a desert area, while Mafraq located in a semiarid area. This is the cause that the beam (direct) solar radiation incident on earth is more for Azraq than for Mafraq. While in summer months (May, June, July, and August), the monthly average daily solar radiation incident on square meter area in Mafraq area is more than for Azraq area; this due the fact that Azraq area has more dust than Mafraq area in summer months, which means that many particles are distributed in the

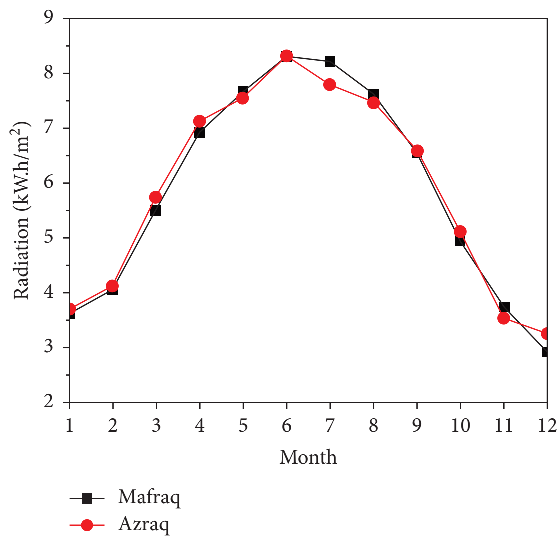

FIGURE 7: Comparison of average daily solar radiation of both site (kWh/m^2.day).

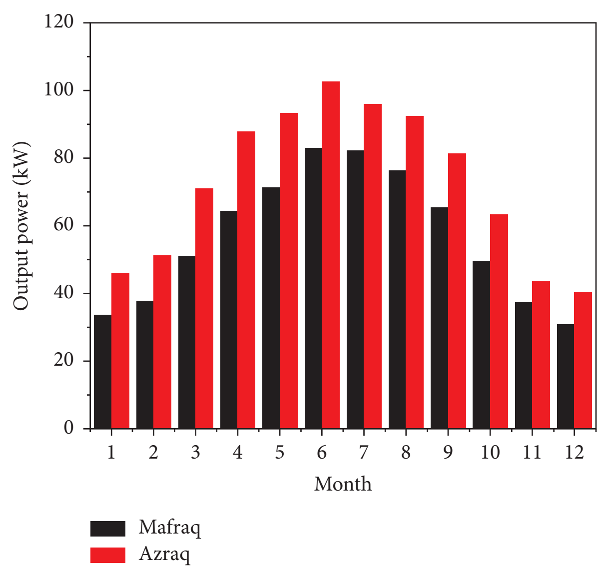

FIGURE 8: Comparison of monthly average output power between both sites.

environment; therefore, the incident solar radiation will have reflected and distributed in the environment and this will lead to decrease in beam (direct) solar radiation incident on earth.

Figure 2 shows the mean ambient temperature in °C. As shown in the figure, the mean ambient temperature for Azraq area is less than that for Mafraq in winter months (December, January, and February), the reason for that is Azraq is located in a desert area that has low temperatures in winter season as compared with Mafraq area, while in the rest of months, the mean ambient temperature for Azraq is more than that for Mafraq as a result of the fact that temperature is high in desert areas than other areas in warm months.

Figure 8 shows the output power from the PV modules at the two selected sites. As shown in the figure, the monthly output power in the Azraq site is greater than that in the Mafraq site. As shown in Figures 2 and 7, the solar radiation and ambient temperature in the Azraq site is more than that in the Mafraq site. This means that the effect of solar radiation on output power is the dominant parameter than the dust and temperature parameters.

6. Conclusion

In this paper, a comprehensive analysis is carried out to draw a comparison of the impact of dust accumulation, ambient temperature, and solar radiation on the performance of polycrystalline PV modules under real outdoor conditions in the arid and semiarid regions of Azraq and Mafraq in Jordan. Azraq has excellent potential for solar power as the modules installed there show higher efficiency. Even the dust deposition rate and ambient temperature are high in Azraq compared with the Mafraq site. The results before show that solar radiation and temperature are higher in the Azraq site than in the Mafraq site. Depending on solar radiation, temperature, and dust, the output voltage and the output power in Azraq is higher than those in Mafraq. The output current in Azraq is less in Mafraq, and this agrees with the state of the art. Depending on the abovementioned results, the Azraq site is more suitable for PV projects compared with the Mafraq site, depending on the three parameters that are taken into account in this research. This conclusion will help the agencies, utilities, and policymaking in the energy sector in Jordan.

Thus, in arid and semiarid land conditions, these parameters should be taken into consideration while sizing the PV solar energy system to avoid any deficiencies in power demand. Higher solar radiation and lower ambient temperature are desired, for optimal performance of PV modules, especially for the crystalline solar PV technology because of the real-life application that the solar PV array will be subjected to.

6.1. Recommendations. PV investigation in Jordan research project has been carried out in two selected sites in Jordan. Depending on results that have been obtained, the following recommendation will be outlined here:

1. Maan site must be included in any similar research in future, where Maan site is the best site in Jordan regarding solar radiation.
2. Dust film must be measured actually in any new research like this one.

Data Availability Statement

Data are contained within the article.

Conflicts of Interest

The authors declare no conflicts of interest.

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