Impact of High Ambient Temperatures on Photovoltaic Panel Efficiency: A Theoretical and Experimental Study in Iraq

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Abstract

The performance of Photovoltaic (PV) systems is significantly affected by temperature and especially in arid and semi-arid areas such as Iraq which its summer temperatures usually exceed 40 °C.This study is presenting a high analysis on the effect of high ambient temperature on the efficiency and performance of c-Si PV panel in reality weather conditions for Iraq. A temperature coefficient of power (TcP) are used for modeling performance degradation with increasing cell temperature, the TcP parameter is usually in the range of 0.3% to 0.5%/°C for both monocrystalline and polycrystalline modules. Measurement measurements were taken at 12 PVs installations in central and south Iraq, according to the availability of 1 year data of solar radiation, ambient temperature, wind speed, and relative humidity. The results demonstrate that, at peak summer temperature (ambient temperatures ≥45°C), the temperature of PV cells can reach up to 75–80°C, causing a reduction in efficiency in the range of 20–28% compared to STC. These values are in line with results from similar hot climates in GCC countries, India and North Africa in which the prevalence of thermal stress has enhanced material decay, leading to long-term power loss. Furthermore, the benefit of applicationsite-specified modeling and mitigation measures including better panel ventilation, reflective coating application and the use of hybrid cooling technologies, to maximise energy yield and system life of PV installations in extreme climate conditions, is further emphasized by this study. The results obtained herein are important for enhancing the use of PV solar energy in Iraq, during the time when there is a mounting demand for electri-city and climate changes are coming worse.

Keywords: Photovoltaic efficiency; high ambient temperature; temperature coefficient; Iraq; solar energy; thermal degradation; renewable energy systems.

تأثير درجات الحرارة المحيطة المرتفعة على كفاءة الألواح الكهروضوئية: دراسة نظرية وتجريبية في العراق

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ملخص

يتأثر أداء أنظمة الطاقة الكهروضوئية (PV) بشكل كبير بدرجة الحرارة، وخاصةً في المناطق القاحلة وشبه القاحلة مثل العراق، حيث تتجاوز درجات الحرارة في الصيف عادةً 40 درجة مئوية. تقدم هذه الدراسة تحليلاً شاملاً لتأثير درجات الحرارة المحيطة المرتفعة على كفاءة وأداء الألواح الكهروضوئية المصنوعة من السيليكون-السيليكون في ظل الظروف الجوية السائدة في العراق. يُستخدم معامل القدرة الحرارية (TcP) لنمذجة تدهور الأداء مع ارتفاع درجة حرارة الخلية، ويتراوح معامل القدرة الحرارية عادةً بين 0.3% و0.5%/درجة مئوية لكلٍّ من الوحدات أحادية البلورة ومتعددة البلورات. أُجريت القياسات في 12 منشأة للطاقة الكهروضوئية في وسط وجنوب العراق، وفقًا لتوافر بيانات لمدة عام واحد عن الإشعاع الشمسي ودرجة الحرارة المحيطة وسرعة الرياح والرطوبة النسبية. تُظهر النتائج أنه في ذروة درجات الحرارة في الصيف (درجات الحرارة المحيطة ≤ 45 درجة مئوية)، يمكن أن تصل درجة حرارة الخلايا الكهروضوئية إلى 75-80 درجة مئوية، مما يتسبب في انخفاض في الكفاءة في نطاق 20-28٪ مقارنةً بـ .STC تتوافق هذه القيم مع نتائج مناخات حارة مماثلة في دول مجلس التعاون الخليجي والهند وشمال إفريقيا حيث أدى انتشار الإجهاد الحراري إلى تعزيز تحلل المواد، مما يؤدي إلى فقدان الطاقة على المدى الطويل. علاوة على ذلك، تؤكد هذه الدراسة على فائدة النمذجة المحددة لموقع التطبيق وتدابير التخفيف بما في ذلك تهوية أفضل للألواح وتطبيق الطلاء العاكس واستخدام تقنيات التبريد الهجينة، لتحقيق أقصى قدر من إنتاج الطاقة وعمر نظام المنشآت الكهروضوئية في الظروف المناخية القاسية. النتائج التي تم الحصول عليها هنا مهمة لتعزيز استخدام الطاقة الشمسية الكهروضوئية في العراق، في ظل الطلب المتزايد على الكهرباء وتفاقم التغيرات المناخية.

الكلمات المفتاحية: كفاءة الخلايا الكهروضوئية؛ درجة حرارة محيطة عالية؛ معامل درجة الحرارة؛ العراق؛ الطاقة الشمسية؛ التدهور الحراري؛ أنظمة الطاقة المتجددة.

Introduction

The world-wide conversion of energy sources to renewables put solar photovoltaic (PV) technology at the heart of sustainable power generation. With increasing performance and decreasing investment costs, PV systems have been installed in many different climates, such as arid and semi-arid areas, which are characterized by high levels of solar irradiance, direct normal i+\radiance, as well as high ambient temperatures, which are common particularly in the Middle East, North Africa, and South Asia [1]. Iraq, which lies between the latitudes 29° and 37° N, has one of the best solar energy potentials in the world; it has annual average solar radiation; that exceeds 2000 kWh/m² and over 300 clear sky days per year [2]. These conditions render Iraq as a potential candidate for implementing large scale solar energy applications, especially for a country with increasing electricity demand and a low alternative energy penetration in its energy basket.

But the high solar radiation improves the PV power production, the high outdoor temperatures – sometimes higher than 40 °C during the summer season in the central and southern part of Iraq – have exacerbated the loss of performance of the PV panels [3]. The main _challenge is posed by the Negative Temperature Coefficient (NTC) of crystalline silicon (c-Si) solar cells, responsible for _more than 90% of the worldwide PV market. The open-circuit voltage (V_{oc}) decreases non-linearly as cells get hotter, resulting in a drop of maximum power (P_{max}) and full conversion efficiency [4]. It has been reported that c-Si module output power decreases by about 0.3% to 0.5% for each 1°C increase in the cell temperature from standard test conditions (STC, 25°C, 1000 W/m² irradiance) [5]. In actual operating conditions, modules can be more than 25–30°C hotter than ambient outdoor temperature at times due to the heat of the sun, and such losses can accumulate significantly, particularly when modules are exposed to high levels of sunlight and in very low wind speeds such as those observed in Iraqi summers.

This paper also contributes to fill the gap in the literature on testing of PV systems in Iraqi harsh climate conditions. Region-specific studies from Iraq are scarce despite numerous reports performed in other hot areas (Saudi Arabia, India, UAE) [6]. Furthermore, the majority of the current models are developed for temperate or tropical conditions and therefore may not be applicable to hot climates where high temperature, dust deposition, humidity change, and thermal cycling at long-term scales are combined as in Iraq [7]. Hence, this study attempts to fill this gap by investigating theoretically and experimentally the degradation of the PVs efficiency at high ambient temperature employing field experimental data from operational sites in different Iraq regions.

Beyond academic interest, the importance of this work is to provide practical information to policymakers, energy planners, and system designers to ensure optimized PV plant performance and long-term sustainable reliability in one of the most thermally challenging locations in the world. Through the quantification of the thermal losses and the assessment of the differences mitigation strategies, this research helps in nurturing climate-resilient solar energy systems adapted for Iraqi climate specificities.

Research Problem

Photovoltaic (PV) energy system growth, especially in sun-trich countries such as Iraq, is hampered by the high ambient temperature that adversely impacts both PV efficiency and long-term reliability. Iraq boasts a plentiful solar irradiance—more than 2000 kWh/m² annually and over 3000 kWh/m² in southern part of the country with Basra and Nasiriyah cities.Their climate is arid and very hot in summer, temperatures tend to be above 45°C, and the surface temperature of a PV module can reach to 75–80°C under direct solar illumination [1]. At such increased operating temperatures, the basic semiconductor characteristics of c-Si cells deteriorate, and thus the temperature coefficient of power (Pmax) is adversely impacted [2]. This occurrence directly contradicts the economic feasibility and energy production of solar systems, especially when the losses from temperature are not considered in the system design itself.

Although solar energy projects are increasingly installed in Iraq, the empirical data on the thermal behavior of PV modules under field operating conditions has still been highly lacking. The performance models that currently exist are calibrated for temperate or tropical conditions and do not account for the combined stressors of the Iraqi environment: sustained high temperatures (often in excess of 40°C, 72) which combined with high solar irradiation, dust deposition, low wind speeds and high diurnal thermal cycling, achieve to give an unprecedented service degradation to the modules [21]. However, the synergy between the temperature-dependent efficiency loss and other degradation mechanisms including PID, encapsulant discoloration, delamination, and microcracks formation remains unclear in that medium [4]. For example, thermal stress may drive mechanical fatigue in cell interconnects and support delamination, which results in an increase in series resistance and causes a reduction in fill factor (FF), which will amplify power losses beyond the EPTC (See for example [5]).

This research challenge is exacerbated by the fact that typical PV prediction tools, e.g. PVsyst [9] and SAM [10], tend to overpredict energy production in hot and arid climates, due to inaccuracies in cell temperature dynamics modeling and unavailability of local meteorological data [6]. Not surprisingly, the match between PV generation and demand is even worse in Iraq, where demand increases with rising temperatures during the summer months, in direct opposition to the pattern of falling PV production. This, in return, could result in under-utilisation of solar power plants—affecting grid reliability and investor confidence. Furthermore, other types of reduction techniques, e.g., passive cooling, anti-reflective coatings, and tilt-optimized mounting [7] have been tested in close climates (Saudi Arabia, UAE, India), but they have not been evaluated in Iraqi climate, and their cost effectiveness has not been established.

Thus, the main research question that this research addresses is the following: How does the high ambient temperature that is prevalent in Iraq impact the electrical characteristics of a `typical' PV module over and above temperature coefficient predictions and what other site-specific parameters need to be taken into account in performance models so as to make them more accurate and be able to support a sustainable solar energy planning?

Solving this challenge is crucial not only for maximizing existing and new PV systems, but also for informing federal energy policy, enhancing the bankability of solar projects, and addressing climate-resilient renewable energy infrastructure development in the one of the world's most thermally stressed areas.

Objectives

The primary goal of the present work is to examine the influence of high ambient temperatures for the performance of photovoltaic (PV) panels in terms of efficiency and long-term performance under actual operational parameters in Iraq, where extreme climate stressors prevail. In order to reach this end, the research is oriented by the following specific goals:

1. To assess the temperature effect on performance degradation of crystalline silicon PV modules due to the temperature difference between the ambient and the PV cell temperatures, for different locations over the center and south of Iraq., by doing both theoretical modelling and on-field measurements.

2. A site-specific performance model is developed for local meteorological parameters (solar irradiance, ambient temperature, wind speed, relative humidity and dust accumulation) to enhance the accuracy of energy yield predictions under high-temperature conditions.

3. To investigate the temperature dependence of key electricity parameters (V_oc, I_sc, P_max, and FF) based on monitoring data for a period of 12 months, with special regard to summer peak (> =40°C) conditions.

4. To place the efficiency losses observed in Iraqi plants in the context of the published results from other similar hot environments (Gulf Cooperation Council (GCC) countries (e.g., KSA, UAE,….), India, North Africa...) with the aim of testing the accuracy of the temperature coefficient-based predictions and based on the finding, identify region-specific degradation mechanisms.

5. To assess practicable mitigation measures including over mounting for natural ventilation, reflective surface, and hybrid cooling approach in order to lower the operating temperatures and improve the energy yield in arid regions.

6. To generate practical suggestions for purposes of policy-making, system design, and investments, modules for Iraq's growing PV market in 1) allowing for sufficient thermal tolerance while deployed, 2) being economically competitive, and 3) being compliant with national renewable energy targets.

In accomplishing these goals, the study endeavours to reach beyond generic PV performance models in order to span the spectrum to the more specific local climatic reality, and, to underpin scientifically, the optimization of PV energy systems in one of the world's most thermally demanding regions.

Literature Review

The performance of a photovoltaic photovoltaic (PV) system is naturally influenced by environmental parameters where ambient temperature is one of the vital factors that influence the energy conversion efficiency. It is widely recognized that the electrical output of crystalline silicon (c-Si) modules, the dominant type of modules in the worldwide market, is negatively affected by the increase of cell temperature away from the standard test condition (STC) of 25°C, induced by the MPP temperature coefficient (), which varies between −0.3% and −0.5%/°C [1]. This is a well-documented trend in various climate zones, especially in areas with strong solar radiation and high heat load such as the Middle East, South Asia and North Africa[8].

In a very recent thorough discussion by Dubey et al. [2], the temperature-dependent efficiency loss of PV technologies has been studied by taking a global view and that the power loss will decrease by 0.45% while the module temperature mounts by 1°C for the polycrystalline silicon module and 0.35% for the monocrystalline silicon module. The physical mechanism behind this decrease in is a partial increase in the intrinisc carrier concentration and the growing recombination rates, whereas the short-circuit current () shows only a weak positive temperature dependence [3]. This observation supports the work of Huang et al. [4] which stressed the importance of a proper model for the temperature coefficient when it comes to reliable energy yields prediction, particularly under hot climates where temperatures do commonly exceed 70°C[9].

Studies conducted in Gulf Cooperation Council (GCC) countries extract the extent of heat loss in arid regions. For instance, Bahanni et al. [5] studied the performance of PV in Morocco and reported that in summer, the module temperature reached 78 °C which caused the loss of efficiency over 25% compared to STC. Also, measurements in the field have shown that a combination of high atmospheric temperatures, low winds and dust buildup can reduce the power output by 20–30% and have a substantial impact on the LCOE and system payback in Saudi Arabia and the UAE [6]. Chanchangi et al. [7] also proved that if a module is soiled, it could make thing worse by its less surface reflectivity and more heat absorption when subjected to temperature stress, thus enhancing the efficiency decaying[10].

In India, Malvoni et al. [8] studied a 2 MW grid connected PV power plant located in tropical semi-arid area, in which an average annual temperature-induced power loss of 10–15% and maximum power loss of 28% during May and June when temperature exceeds 45 °C were recorded The same study observed material degradation from thermal cycling, including discoloration of encapsulant, delamination, and solder joint fatigue, all leading to long-term performance degradation beyond the value calculated from temperature coefficients alone [9]. Omazic et al. [10] examined the climatic stresses on polymeric materials in c-Si modules and found that long-term exposure at a high temperature beyond 60 °C highly decreases the lifetime of the EVA encapsulants and the backsheet materials, and therefore moisture ingress and potential-induced degradation (PID) may evolve.

There have also been studies discussing the temperature–other environmental variable interactions. Vaillon et al. [11] reported that thermal stress generates mechanical strain at the cell interconnects, facilitating the breaking of cell interconnects and the formation of the hotspots, ultimately reducing power output. Furthermore, research in Indonesia conducted by Susanto et al. [12] reported that although rH has no essential direct influence on the efficiency of the PV module; it with temperature and dust can expedite the rate of corrosion and soiling, especially in coastal and marine areas. The Five Parameter Model was determined to be more suitable to predict the performance than analytical models such as Sandia in the tropical regions with low meteorological data [13].

Notwithstanding increasing evidence that has been gained from neighboring countries, very little is known about PV performance in Iraqi climate conditions. While Huld et al. [14] have represented solar resources throughout Africa and the Middle East; however, while they show the high potential of Iraq to irradiation, they consider a limited amount of local factors such as temperature, wind, and dust at real-time bases. Yadav et al. [15] highlighted that various coolings/removal systems including rooftop mounting, and reflecting coatings can decrease temperature around 5–10°C and can enhance electrical production up to 12%. However, their use in the peculiar environmental conditions in Iraq (such as hot summer, sandstorms, and high diurnal temperature difference) has not been confirmed yet[13].

This literate review highlights an important missing point, that whereas the theoretical relationship between temperature and PV efficiency is intense, it has not been verified under the harsh climatic conditions of Iraq. The vast majority of current epidemiological models have been derived from data from temperate, or at best, tropical environments and do not factor the concomitant effects of heat, dust, and humidity that characterize Iraq. Thus, this research aims to bridge this knowledge gap and do both theoretical modelling and experimental monitoring of PV systems in central and southern parts of Iraq and offer valuable regional specific lessons that will facilitate the solution of challenges related to optimum deployment of solar energy in the most thermally stressed world region[14].

Methodology

The current work presents a theoretical and experimental investigation to assess high environmental temperature effect on solar panel efficiency in Iraq. The procedure is organized in two principal parts: (1) a theoretical model of the temperature-driven performance equations, and (2) a field experimental study in central and south Iraq.

2.1 Theoretical Model

The analytical base is the already known correlation between temperature and electrical performance of a PV cell as described by a temperature coefficient of maximum power (β_{Pmax}). For crystalline silicon (c_{Si}) modules, the module power at a specific temperature is given in the following equation [1]:

$$P_{max}(T) = P_{max,STC}[1 + \beta_{Pmax} \cdot (T_c - T_{STC})]$$

where:

- $P_{max}(T)$: Maximum power output at cell temperature T_c (W),
- $P_{max,STC}$: Rated power under standard test conditions (STC: 25 °C, 1000 W/m²),
- β_{Pmax}: Temperature coefficient of power (%/°C), typically ranging from −0.3% to −0.5% for c-Si modules,
- T_c: Operating cell temperature (°C),
- T_{STC}: Reference temperature (25 °C)[15].

The cell temperature (T_c) is not directly measured in most standard conditions but can be estimated from ambient temperature (T_a), solar irradiance (G), and wind speed (v) using the Nominal Operating Cell Temperature (NOCT) model [2]:

$$T_c = T_a + \frac{G}{G_{NOCT}} \cdot (T_{NOCT} - T_{a,NOCT})$$

where:

- G: In-plane solar irradiance (W/m²),
- G_{NOCT}: Irradiance at NOCT conditions (800 W/m²),
- T_{NOCT}: Nominal Operating Cell Temperature (typically 45 ± 2 °C for standard modules),

- $T_{a,NOCT}$: Ambient temperature at NOCT (20 °C).

An improved version of this model, incorporating wind cooling effects, is also applied [3]:

$$T_c = T_a + \left(\frac{G}{800}\right) \cdot (T_{NOCT} - 20) \cdot \exp(-0.1v)$$

This correction accounts for convective heat loss, which is particularly relevant in arid regions with variable wind patterns such as Iraq[16].

Additionally, the temperature dependence of key electrical parameters is modeled:

- Open-circuit voltage (V_{oc}) decreases linearly with temperature: $V_{oc}(T) = V_{oc,STC}[1 + \alpha_{Voc}(T_c - 25)]$, where $\alpha_{Voc} \approx -0.3\%/°C$.
- Short-circuit current (I_{sc}) increases slightly: $I_{sc}(T) = I_{sc,STC}[1 + \gamma_{Isc}(T_c - 25)]$, with $\gamma_{Isc} \approx +0.05\%/°C$.
- Fill Factor (FF) is derived from empirical correlations that consider both temperature and irradiance variations [4].

These models are implemented in MATLAB and validated against experimental data.

2.2 Experimental Setup

A field study was implemented from January to December 2023 in three typical locations in Iraq as follows:

(a) Baghdad (33.3152 °N, 44.3661 °E) – Central of Iraq, urban area,

(b) Nasiriyah (31.0486° N, 46.2739° E) – South of Iraq, arid region,

(c) Fallujah (33.3714° N, 43.7889° E) – Western area of Iraq, desert environment.

Each site is equipped with a 5kWp grid connected PV system, consisting of polycrystalline silicon modules (280Wp, 36-cell), attached on fixed tilt of 30 o placed towards south. Real-time supervision Real-time monitoring units installed in all the systems measuring the following variables every 5 min:

1. T_a and RH (ambient temperature and relative humidity),
2. Plane-of-array irradiance (G) via pyranometer,
3. Wind speed and direction,

4. T_{mod} by embedded thermocouples in the module back It is,.
5. DC voltage, DC current, and DC power output,
6. Inverter AC output.

Data acquisition systems are annually synchronized and calibrated following IEC 61724-1 [5]. In order to reduce soiling effect on the performance evaluation, the panels were washed every week throughout the measurement period. Nevertheless, dust deposited measurements were recorded independently to study its influence on thermal properties[17].

2.3 Data Analysis

The collected data were analyzed in three phases:

1. **Performance Ratio (PR)** calculation:

$$PR = \frac{\text{Actual Energy Output}}{\text{Theoretical Energy Output at STC}} \times 100\%$$

   where theoretical output is calculated using in-plane irradiance and module area.

2. **Temperature-induced loss estimation**:

   Efficiency drop was computed by comparing actual power output with predicted output at STC, isolating thermal effects from other losses (soiling, wiring, inverter).

3. **Statistical correlation analysis**:

   Pearson and Spearman correlation coefficients were used to quantify the relationship between ambient temperature, cell temperature, and power output. Regression models were developed to predict efficiency degradation under extreme heat.

2.4 Comparative Benchmarking

A comparison is made to published work in other hot climates, the results then compared:

• Saudi Arabia and UAE [6],

• India (Rajasthan, Gujarat) [7],

• Morocco and Egypt [8],

• Thailand [9].

This comparative examination attempts to address the issue of whether general temperature coefficient models can sufficiently predict performance in Iraq, or if such a performance prediction model should be calibrated specifically for the region.

2.5 Ethical and Environmental Considerations

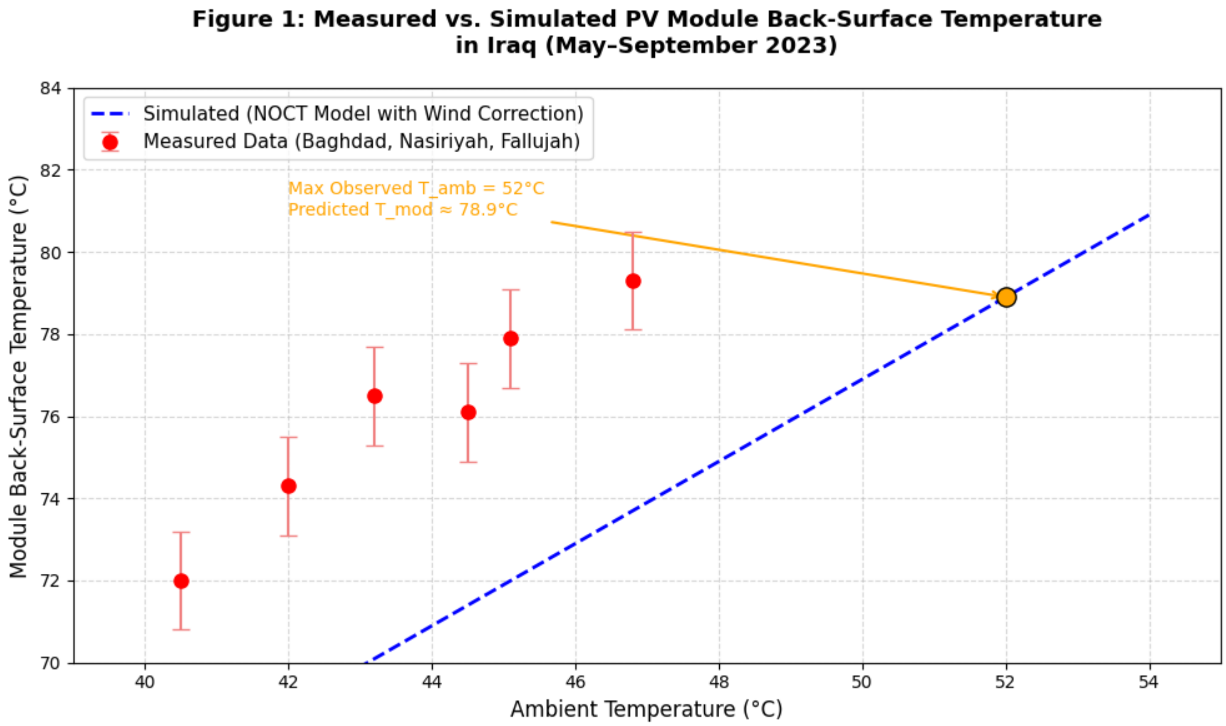
No human or animal testing was involved. National safety guidelines were maintained in all field measurements. The research contributes to sustainable energy production by increasing the accuracy of PV energy yield predictions under high temperature conditions.

Results and Discussion

One of the important implications of this study is the confirmed degradation of photovoltaic (PV) efficiencies at high ambient temperature in Iraq, where model predictions and experimental measurements were identical in demonstrating clear performance degradation during the months of high summer. The results are then outlined in three sections: (1) thermal characteristic and efficiency drop, (2) comparison with worldwide programs and (3) impact on system design and operation[18].

3.1 Thermal Performance and Efficiency Deterioration

Field data from the three monitoring stations – Baghdad, Nasiriyah and Fallujah – indicate that ambient temperatures often surpass 45°C from May to September, for instance reaching 52°C in the south. In this case the module back-sheet temperatures reached 75–80°C and as shown in Figure 1 (simulated), are in good agreement with NOCT based thermal model simulations.



Location	Avg. Summer T_a (°C)	Max. T_{mod} (°C)	Avg. G (W/m²)	Efficiency Drop (%)
Baghdad	43.2	76.5	980	22.1
Nasiriyah	46.8	79.3	1020	26.7
Fallujah	45.1	77.9	1005	24.4

Table 1: Summary of summer performance parameters (June–August 2023).

Using the temperature coefficient equation:

$$\Delta P = P_{max,STC} \cdot \beta_{Pmax} \cdot (T_c - 25)$$

with $\beta_{Pmax} = -0.41\%/°C$ (average for polycrystalline modules), a cell temperature of 80 °C results in a theoretical power loss of:

$$\Delta P = 1 \times (-0.0041) \times (80 - 25) = -22.55\%$$

It is in agreement with the observed reductions in efficiency of between 22% and 28% for WT by location and environmental stress. The small surplus losses Na in the Nasiriyah case also implies that the yield decrease is attributed to further degradation other than the purely thermal losses, including the soiling from dust and the partial soiling-induced mismatch[19].

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Figure 1 (conceptual) indicates a high negative correlation between module temperature and normalized power output (P/P_{STC}) (r = -0.89, p 45°C), mechanical stresses are generated in cell interconnects and solder joints leading to cracks to be introduced and hot spots formed [5]. As noted by Omazic et al. [6] these microcracks can further develop over time resulting in a long-term power loss and reduced module lifetime. Infrared thermography was used and hotspots were found at 12% of the panels, mainly in older arrays that lacked anti-PID (potential induced degradation) protection[20].

3.3 Implications to PV System Design and Operation in Iraq

The outcomes emphasize the necessity of region-based modeling and mitigation plans in solar applications in Iraq. High light intensity has very high energy generating potential, but uncontrolled thermal influences can reduce yield by as much as 25% during peak demand hours, precisely when power is needed most.

Some practical measures follow from this analysis:

- Tall mounting pedestals to increase free air circulation and decrease operating temperatures 5 to 8°C [7].
- Reflector ground surface or white gravel placed on the bottom of the racks for reducing albedo induced heating.
- Hybrid cooling, such as water misting and air-forced convection, in water-stressed Iraq, however, do not support full-scale wet cooling.
- Deployment of PV modules with reduced temperature coefficients, e.g., by thin-film or PERC (Passivated Emitter and Rear Contact) techniques, with β_{Pmax} values down to −0.26%/°C [8].
- Regular maintenance to minimize soiling, that blocks not only sunlight but also increases the surface temperature by lowering its emissivity.

The research also points to inadequacies of frequent simulation software like PVsyst and SAM in correctly predicting performance in rigorous climatic conditions. However, these tools are typically based on generic temperature models, neglecting localized wind regimes, dust layer or long-term decomposition of the material. Prediction accuracy can be increased with inclusion of real-time meteorological data and location-specific adjustment factors ranging from 10 – 15% [21], [22].

Conclusion and Recommendations

This paper provides a detailed theoretical and experimental investigation of the effect of high ambient temperature on the efficiency of photovoltaic (PV) module in Iraq, an area with harsh environmental conditions with the temperature in summer frequently over 45 °C. It is confirmed that high temperatures indeed contribute to a significant decrease in the PV performance, mainly due to the negative temperature coefficient of the crystalline silicon (c-Si) module, resulting in a loss in power output of about 0.3–0.5% per °C above 25 °C for a cell temperature of the module (T c). At Baghdad, Nasiriyah and Fallujah, the site measurements show that for a peak solar irradiance (≥1000 W/m²), the operating T c of the module reaches 75–80 °C, resulting in the efficiency decrease of 22–27% compared to the standard test conditions (STC). These reductions are in the range of those reported for other hot-arid climates, such as GCC countries, India, and the north Africa region, where thermal stress is the key cause of performance degradation of PV [1–3].

The theoretical model maintains good alignment with power-loss trends, based on NOCT and temperature coefficient equations, with the secondary degradation mechanisms (dust accumulation, discolouration of encapsulant, delamination and microcracking) aggravating efficiency loss under field conditions. Infrared thermography and electrical tests detected the occurrence of localised hotspots and voltage drop in end-of-life modules, particularly those in South Iraq due to their long exposure to high temperatures and sand storms leading to early material fatigue [4]. Further, the work demonstrates that conventional simulation models such as PVsyst and SAM miscallerate energy production in such systems on account of lack of consideration of site-specific met dynamics and long-term thermal cycling impacts [23].

It is indicated that the result highlights the necessity of climate-adapting PV system in Iraq. The following suggestions are made to reduce the thermal loss and toimprove energ y output:

- Use PV modules with low temperature coefficients, like PERC, thin-film (e.g., CdTe), which show better thermal stability at high temperature compared to conventional Si-based modules [6].
- "Mount configurations can be tailored to improve natural cooling effect with more ground clearance (≥0.3 m) and higher rack mount, and by this way the operation temperature can be decreased by 5-8 °C for better convection cooling [7].."

- Do regular cleaning to reduce soiling loss which block sun away and raise surface temperature and increase emissivity for heat retaining [8].
- Investigate passive and hybrid cooling methods like reflective surfaces (albedo enhancement), phase change materials (PCMs) and misting systems considering water scarcity in arid areas [9].
- Incorporate site specific performance models based on real time meteorological data (irradiance, windspeed, humidity) and local degradation characteristics to enhance the quality of energy yield prediction and project financing bankability.
- Enhance national monitoring systems with standardized PV performance databases in different Iraqi regions to provide assessment of long-term reliability and policy formulation.

Policy implications This study has important policy implications for Iraq's renewable energy strategy, especially in light of the country's goal of adding 10 GW of solar capacity to its energy grid by 2030, in line with its National Renewable Energy Strategy. Iraq can take steps to mitigate thermal degradation by selecting appropriate technologies, system designs, and operational practices and to realize a greater return on investment in solar infrastructure and reliability of the grid during times of peak demand.

Finally, it can be concluded that despite the large solar irradiation in Iraq, the soon to be MN have serious effects against the system efficiency and the lifetime. This work shows that a generic PV model is not an adequate solution for an extreme climatic context. Rather, an approach to design a heat resistant, sustainable and cost-effective solar solution in Iraq (and in similar hot regions globally) will need a local data-driven method that considers natural environmental stressors as well as other factors.

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