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Analysis of the Optimal Performance Point Concerning Ambient Temperature and Irradiance for an Off-Grid System in Comparison to Standard Conditions in a PV Power System

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Abstract

Aim: Researchers are establishing the challenges associated with power plants of photovoltaic energy systems to enhance their adaptability, durability, and ecological sustainability, aiming to make significant advancements that address current deficiencies in solar energy technology. This study aims to evaluate the performance of an off-grid photovoltaic system (4175 kWP) under varying irradiation and ambient temperature conditions, to determine their effects on system efficiency and global losses.

Methods: Using a simulation model (PVsyst/Matlab/experimental setup), we analyzed system performance under different environmental conditions. The study focused on ambient temperatures of 20°C, 30°C, and 35°C, with irradiation levels of 500, 600, 700, and 800 W/m², in comparison to the standard conditions established by the photovoltaic system, which are 1000 W/m² irradiation and an ambient temperature of 25°C.

Results: The performance at 30°C was 3465.9 kW with a loss of 16.8%, and at 35°C, the Pmpp was 3388.3 kW with an 18.6% loss.

Conclusion: These results underline the necessity of factoring site-specific climatic conditions when designing off-grid PV systems to ensure optimal efficiency and reduced energy losses.

Recommendation: Future studies should incorporate additional external variables, such as wind velocity and incidence angle, to develop a more comprehensive model of PV system performance.

Keywords: *Ambient temperature, global loss, irradiation, off-grid system, solar photovoltaic maximum power point (pmpp), pv efficiency, system performance modeling.*

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INTRODUCTION

Photovoltaic (PV) energy has gained significant importance in recent years due to its role as a clean, sustainable, and reliable renewable energy source. It is abundant, environmentally friendly, and has low operating costs, making it a key technology for global energy transitions [1]. Solar energy is characterized by abundant, safe, and non-polluting source of energy that is renewable [2]. Solar PV panels have a long lifespan of about 20 years and low maintenance costs [4],[5], have ability to install and operate in mountainous geographical conditions, suitability for mobile systems, easy maintenance, independence from the grid in remote locations, and connectivity to the grid. These features provide a promising future for these systems [6]. The considerable common solar photovoltaic systems involve the (i) Large-Scale and Small-Scale solar PV systems, (ii) Off-grid and On-grid Solar PV Systems (iii) Hyper Solar PV Systems(iv) Solar Water Pumping Solar PV Systems(v)Solar Street Lighting Solar PV Systems(vi) Solar Heating Solar PV Systems(vii)Self-Charging Solar PV System

Generally, solar energy can be harnessed in several ways to produce electrical, thermal, or mechanical energy [7]. Among these, solar photovoltaic (PV) energy has gained massive importance in the global energy sector. PV systems are being installed at an unprecedented scale worldwide [8],[9],[10]. The crucial role of solar photovoltaic energy and its central position in the energy transition have made it a widely accepted and increasingly vital energy source. This growing significance has prompted countries across the world to focus more on photovoltaic technologies, with reliance on them increasing year after year.

Figure 1 and Figure 2 illustrates modern solar energy generation in comparison with other renewable energy sources in 2023, measured in terawatt-hours, while Figure (2) highlights the acceleration rates of solar PV expansion projected from 2024 to 2025, particularly in electricity generation. By 2028, solar photovoltaics are expected to account for 12.6% of all renewable energy utilization [11],[12]. Moreover, global solar PV installations are anticipated to reach between 5,457.5 and 6,101.6 GW by 2030, representing a 3.86–4.32-fold increase from 2023 levels [13],[14],[15].

Looking further ahead, the total power output generated by PV is projected to reach 14.5 TW worldwide by 2050 [16],[17]. The rapid growth of solar photovoltaic technologies signals significant developments in the coming decades. By 2100, it is envisioned that nearly 85% of global energy production will rely on solar photovoltaics. This trajectory will be driven by continuous advancements in research and development such as improving solar cell efficiency, addressing internal and external performance limitations, and providing sustainable solutions for hazardous waste generated by damaged or end-of-life PV panels.

However, this transition may contribute to creating a sustainable energy landscape capable of addressing the challenges currently encountered in solar photovoltaic systems, while simultaneously promoting their development toward a long-term future that could extend for thousands of years. In this regard, solar PV has the potential to serve as a reliable renewable alternative to conventional primary energy sources [20],[21]. While numerous studies have emphasized the expansion and economic potential of solar photovoltaics, relatively fewer have explored the technical performance challenges particularly the influence of environmental factors such as solar irradiation and temperature on PV system efficiency and reliability. The objective of this study is to investigate how variations in solar irradiation and ambient temperature affect the maximum power point (PMPP) of photovoltaic arrays. Specifically, we

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aim to: (i) compare performance under standard test conditions and real-world conditions, and (ii) evaluate the implications of environmental variability on PV system efficiency.

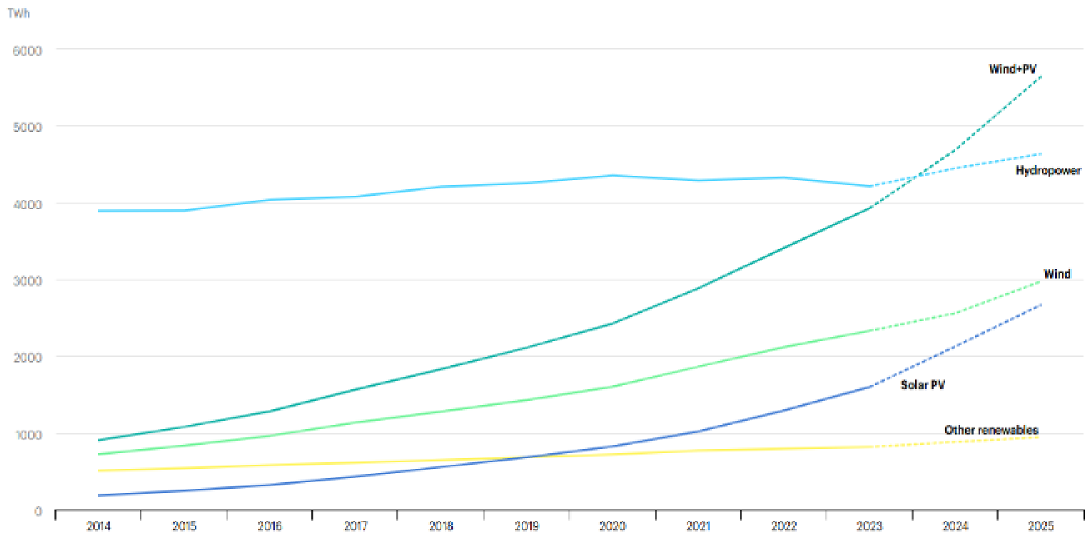

Figure 1: Sources of Modern Renewable Energy Production Worldwide [18].

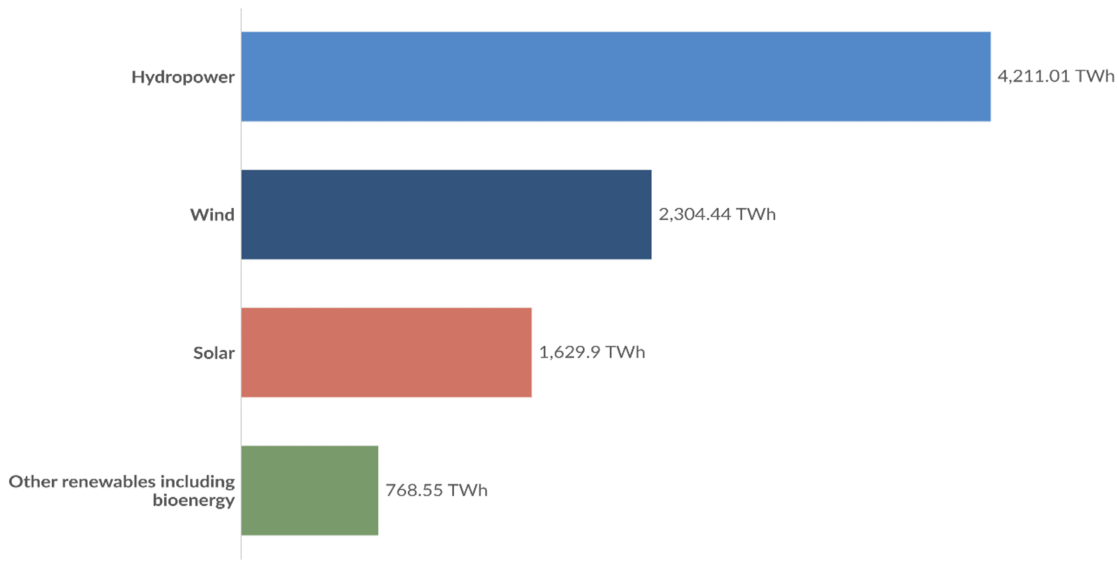

Figure 2: Sources of Renewable Energy for Producing Electricity Between 2014 and 2025 [19].

LITERATURE REVIEW

A comprehensive Overview of the PV System

Previous studies have examined various aspects of photovoltaic (PV) energy systems, including their effectiveness, installation for diverse applications, and their role in reducing dependence on fossil fuels while contributing to environmental sustainability. These investigations have covered stand-alone, grid-connected, and hybrid PV configurations, all of which are considered pivotal in establishing a sustainable pathway for future energy. The studies can be grouped into several thematic areas, as follows:

Several studies emphasize the economic feasibility and environmental benefits of PV systems. For instance, off-grid PV systems in Punjab were found to be both cost-effective and capable of mitigating substantial CO_2 emissions [22]. Similarly, solar-powered grass-cutting equipment modeled in PVSYST demonstrated superior environmental performance compared to diesel alternatives [23]. These studies highlight PV's role as a cleaner, renewable alternative to conventional energy solutions.

Numerous works focus on designing and simulating stand-alone PV systems to meet specific load requirements. Examples include system design for the Mechanical Department in Bikaner [24], feasibility studies in M'sila, Algeria [25], and SAPV systems simulated to predict annual energy generation and optimal sizing [27]. In Iraq, multiple studies analyzed SAPV designs for Mandali City households [42] and for laboratories at Al-Nahrain University, Baghdad, ensuring continuous power supply [43]. Other projects, such as the standalone PV system for Dina Farm Rest in Egypt [39], provided insights into energy generation, efficiency, and component selection for rural and agricultural applications.

A significant number of studies have evaluated grid-connected PV installations in academic, industrial, and urban contexts. Examples include a grid-connected silicon-poly PV system (20 kW) supplying electricity to an academic institution [24], a 100 kWp system for an educational institute [35], and a large-scale 1 MW installation in Shapur, Gujarat [33]. Additional studies include the design of a 400 kWp system in Bahteem, Egypt [32], an 81.9 kWp rooftop system on academic buildings monitored over 12 months [29], and a 115.2 kWp solar plant at Tribhuvan University Teaching Hospital in Kathmandu, Nepal [38]. In rural Uttar Pradesh, India, a 60 kWp on-grid PV plant was designed using seasonal tilt angles for optimal performance [40]. Furthermore, rooftop solar PV systems for academic campuses have been shown to supply significant portions of energy demand while reducing CO_2 emissions [41].

Hybrid approaches have also been investigated, particularly for improving reliability under variable generation conditions. One study proposed an optimal sizing strategy for stand-alone PV systems under worst-case scenarios [30]. Another explored a "PV + energy storage" system that considered power generation, storage demand, and environmental impacts to improve economic efficiency and reliability [34]. In Jordan, a floating PV water pumping system was designed and optimized, integrating technical, environmental, and economic considerations to yield a highly efficient 165 kW installation [37].

Many studies have utilized PVSYST software to simulate, optimize, and validate PV system performance. For example, a 1 MW plant in northern Morocco was modeled to evaluate feasibility and performance ratios [28]. Real-time monitoring of the 81.9 kWp rooftop system confirmed the reliability of PVSYST predictions, with observed seasonal variations in efficiency and energy yield [29]. Similarly, a 1 kWp PV system in Hamirpur, India, achieved a performance ratio of 0.724, validating its long-term viability [31]. Studies in Iraq (Karbala and Erbil Provinces) examined optimal tilt angles, finding improved production efficiency with adjustments to 31° and 33°, respectively [6]. Across these works, PVSYST consistently emerges as a dependable tool for predicting PV system efficiency, yield, and losses [36].

Collectively, these studies demonstrate that solar photovoltaic systems are being widely investigated across diverse contexts, from household and agricultural applications to large-scale grid-connected plants and hybrid configurations. While results consistently indicate their economic viability, environmental benefits, and technical reliability, they also highlight performance variations influenced by environmental factors such as temperature and irradiation. This body of literature underscores PV's growing role in global energy transitions, while also revealing the need for continued research into optimizing technical performance, improving storage integration, and addressing system-specific challenges.

Review Studies of Previous PV-System Simulations

We further elaborate on previous studies that simulated photovoltaic systems using PVsyst software (Table 1). These studies explored diverse applications and purposes, tailored to specific geographical and environmental conditions across different regions of the world. As shown in Table 1, grid-connected PV systems dominate, particularly in urban and institutional settings, owing to their relative cost-effectiveness, ease of integration into existing infrastructure, and capacity to offset electricity costs. In contrast, stand-alone PV systems, while less common due to their higher initial investment and maintenance costs, remain indispensable for rural electrification and locations where grid access is limited or unavailable. Overall, the reviewed studies demonstrate PVsyst's versatility as a modeling tool for assessing performance ratios, energy yields, losses, and optimization strategies in both grid-connected and stand-alone configurations.

Table 1: Summary of PVsyst-based Simulation Studies on Photovoltaic Systems

SI. No	Tilt/Azimuth	Nominal PV power	Site	Type	Software	Year	Ref
1	25°/20°	14.8 KWp	Karunya Institute of Technology	Grid-connected	PVSyst	2023	[44]
2	27°/0°	3.3 KWP	Tetulia, Panchagrah, Bangladesh	Grid-connected	PVSyst	2022	[45]
3	32°/0°	4 KWP	Mandali City	Stand-alone	PVSyst	2024	[46]
4	30°/0°	999 KWP	Salah al-Din	Grid-connected	PVSyst	2024	[47]
5	33°/0°	9.9 KWP	Darab and Meybod in Fars and Yazd	Grid-connected	PVSyst	2023	[48]
6	30°/-20°	19916 KWP	Cairo International Airport	Grid-connected	PVSyst	2021	[49]
7	30°/0°	960 KWP	AI Juaima'h, Dammam	Grid-connected	PVSyst	2022	[50]
8	34°/0°	6399 KWP	Ghor	Grid-connected	PVSyst	2022	[51]
9	15° /180°	2.5 KWP	Karnataka	Stand-alone	PVSyst	2018	[52]
10	13°/0°	0.3 KWP	Daily Household consumption	No sizing	PVSyst	2020	[53]
11	30°/0°	641KWP	Kţbīyah	Grid-connected	PVSyst	2025	[54]
12	30°/0°	30.0KWP	Al Qattarah	Grid-connected	PVSyst	2025	[55]

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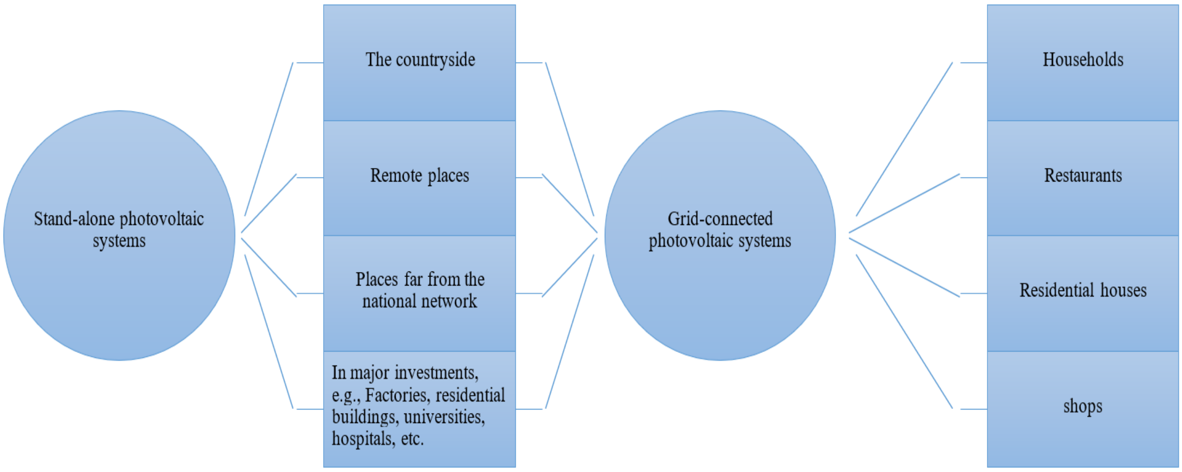

Figure 3: Optimal Applications of PV systems

Figure 3 shows the most prominent applications in which connected and independent photovoltaic energy systems can be used. This is based on the applications that have been implemented in recent years and are still ongoing. On the other hand, stand-alone systems effectively deliver reliable electricity in remote areas and areas far from the grid [56].

MATERIAL AND METHODS

In this work, photovoltaic modules of type JKM585M-7RL4-V and battery model DCB102Z were employed. Accordingly, Tables (2) and (3) present the PV array characteristics of the off-grid photovoltaic system.

Photovoltaic (PV) Technology

Photovoltaic (PV) technology represents a vital innovation capable of directly converting solar radiation into electrical energy through PV panels [5],[58],[59]. Unlike other conversion methods, PV conversion bypasses heat engines, making the process highly efficient and direct. PV devices are characterized by their ruggedness, simplicity of design, and minimal maintenance requirements. Their major advantage lies in their versatility, as they can be constructed as stand-alone systems with outputs ranging from microwatts to megawatts.

Consequently, PV technology has been applied in a wide variety of contexts, including household power supply, water pumping, remote buildings, solar home systems, communication networks, satellites, space vehicles, reverse osmosis plants, and even megawatt-scale power plants. A photovoltaic power generation system typically consists of solar cells, mechanical and electrical connections, structural mountings, and devices for regulating and/or modifying the electrical output. These systems are generally rated in peak kilowatts (kWp), which denote the maximum amount of electrical power a system can deliver when the sun is directly overhead on a clear, cloudless day [60].

Analysis of the PV Off-Grid System

For the present study, PVsyst software was employed to model and analyze the performance of an off-grid photovoltaic system. A recurring question among engineers and researchers concerns why standard test conditions of 1000 W/m² irradiation and 25°C temperature is typically chosen. To investigate this issue, we designed a system to evaluate the influence of solar irradiation and ambient temperature, as these are among the most significant external factors affecting the efficiency of PV modules.

The study was conducted in Al Mu'tadilah, Iraq (Latitude: 32.89°N, Longitude: 41.52°E, Altitude: 454 m, Time zone: UTC+3), based on PVsyst simulations. This evaluation was carried out to address the growing concern regarding the volatility of environmental conditions in Iraq, which often exerts a negative impact on the performance of PV units in the collector field. By examining the impact of individual loss factors on the PV array, the study provides important insights into modern approaches that could enhance PV system performance and contribute to solving challenges associated with photovoltaic energy systems.

Table 2: The Main Characteristics of the Module

PV Module	Units
Manufacture	Jinkosolar
Model	JKM585M-7RL4-V
Unit Nom. Power	585 Wp
Number of PV modules	7136 units
Modules	892 Strings x 8 In series
At operating cond. (50°C	
Pmpp	3809kWp
U mpp	322 V
I mpp	11820 A

Table 3: The Main Characteristics of a Battery

Battery	Units
Manufacturer	Panasonic
Mode	DCB102Z
Technology	Lithium-ion, LCO
Nb. of units	5000 in parallel x 5 in series
Discharging min. SOC	10.00%
Stored energy	58441.5 KWh
Battery Pack Characteristics	
Voltage	241 V
Nominal Capacity	270000 Ah (C10
Temperature	Given monthly values

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RESULTS AND DISCUSSION

The stand-alone PV system was simulated using PVsyst software to evaluate the effects of irradiation and ambient temperature on system performance. The following results summarize the variations in energy yield, efficiency, and system losses under different environmental conditions. The primary objective of this work was to identify the most critical external factors influencing PV system performance and to analyze their impact on the energy production rate of an independent photovoltaic station. Importantly, although the case study was conducted in Iraq, the findings are applicable to other regions with similar climatic conditions, thereby broadening the relevance of this work beyond a single geographic context.

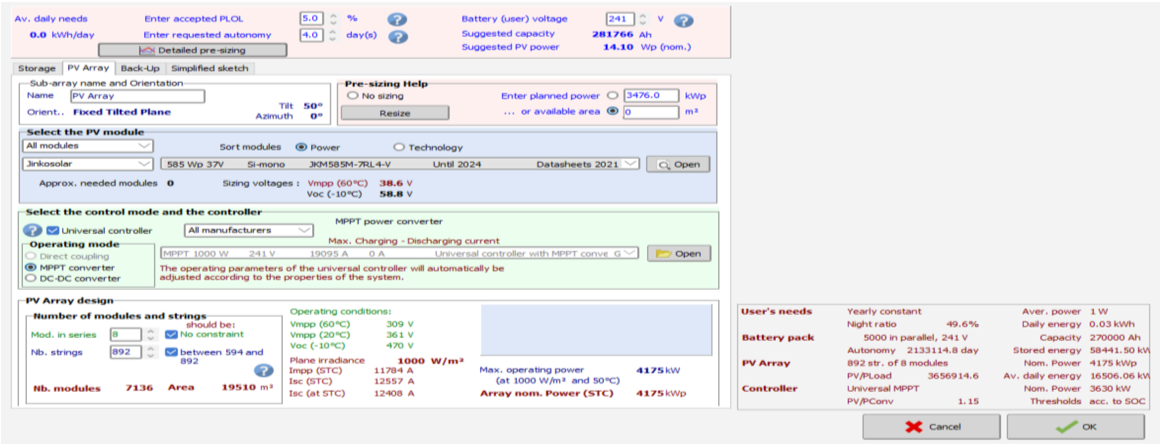

Figure 4: Board for PV-Off-grid System

Figure 4 illustrates the schematic configuration of the simulated off-grid PV system, showing the arrangement of modules and the integration of battery storage. This configuration served as the basis for performance evaluation.

Table 4 provides a synopsis of the system results, highlighting the main performance parameters derived from PVsyst. These average values reflect the essential characteristics of the designed system and establish a validated methodology for performance assessment. The simulation emphasized a stand-alone configuration with fixed user demand, constant load capacity of 1 W, and an annual global production of approximately 10.0 kWh/year.

Table 4: Synopsis of System Results

Parameter	Units
Available Energy	7354188 kWh/year
Used Energy	10 kWh/year
Specific production	1762 kWh/kWp/year
Perf. Ratio PR	0.00%
Solar Fraction SF	100.00%
Orientation	
Tilt/Azimuth	50 / 0 °
Nb. of modules	7136 units
Pnom total	4175KWP

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Analysis of Simulation Results

To investigate system performance, simulations were conducted under varying levels of irradiation and ambient temperature. The results reveal a clear dependence of system output on environmental conditions. At lower ambient temperatures (e.g., 20°C and 25°C), the maximum power point (Pmpp) increases, indicating higher system efficiency, although the overall global losses are comparatively higher. At higher ambient temperatures (e.g., 30°C and 35°C), the system exhibits reduced Pmpp values, reflecting the well-documented negative impact of elevated temperatures on PV performance. The results also demonstrate that under increasing irradiation levels (500, 600, 700, 800, and 1000 W/m²), system performance improves in terms of energy yield; however, efficiency gains are tempered by higher thermal loads at elevated temperatures. Figure 5 presents the simulation outcomes under different ambient temperature conditions, while Table 7 provides the results for varying irradiation levels, offering a detailed sensitivity analysis of PV system behavior.

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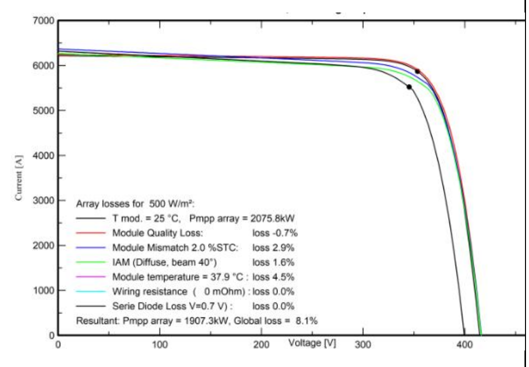
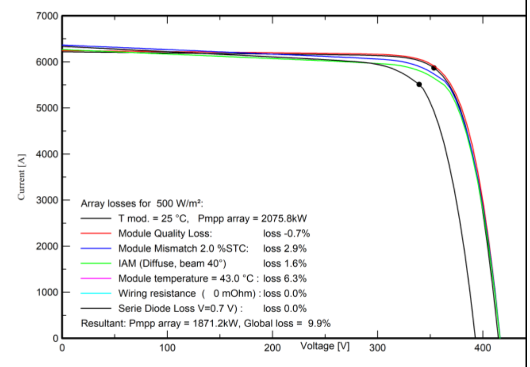
<tr><td>500w/m²</td><td>
</td><td>
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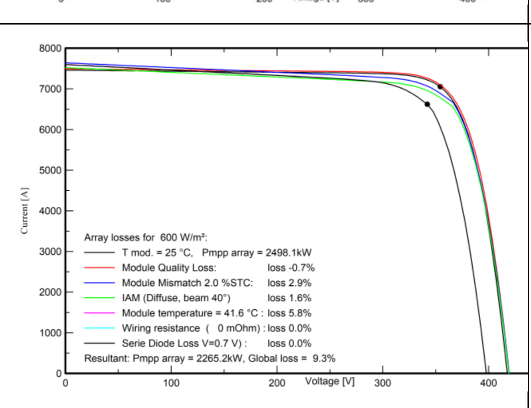
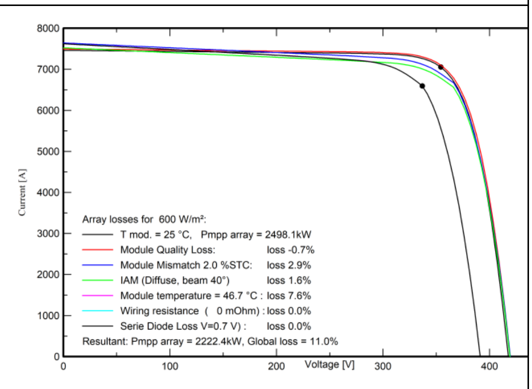
<tr><td>600w/m²</td><td>
</td><td>
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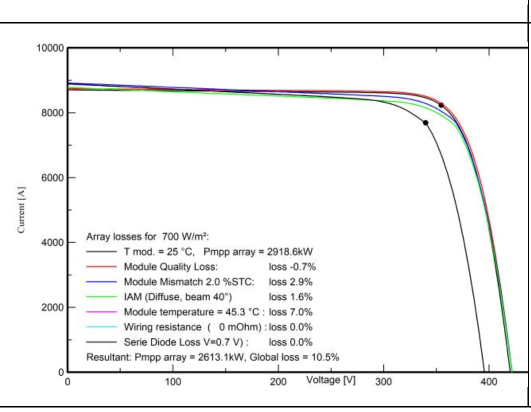
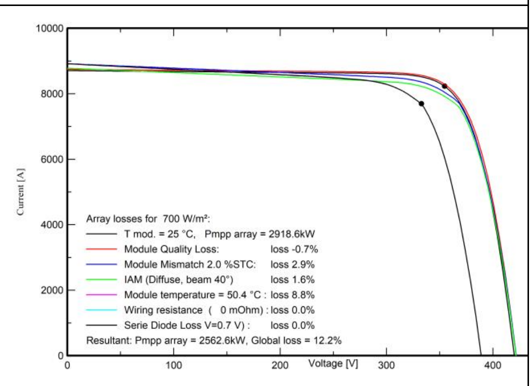
<tr><td>700w/m²</td><td>
</td><td>
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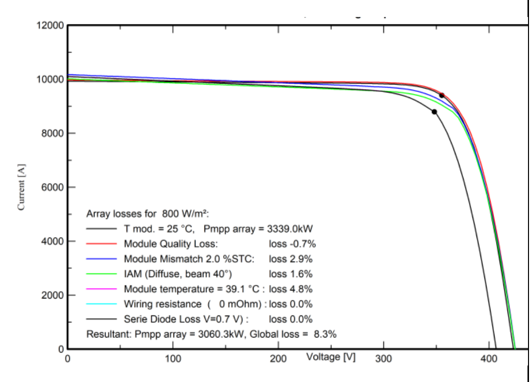

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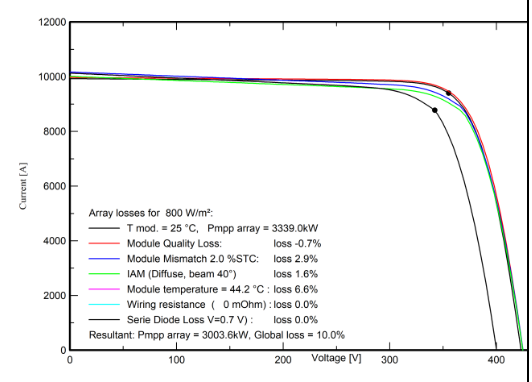

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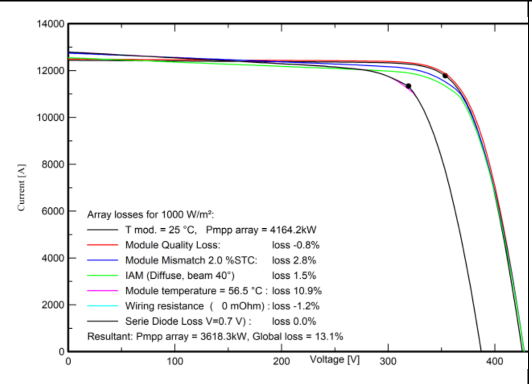

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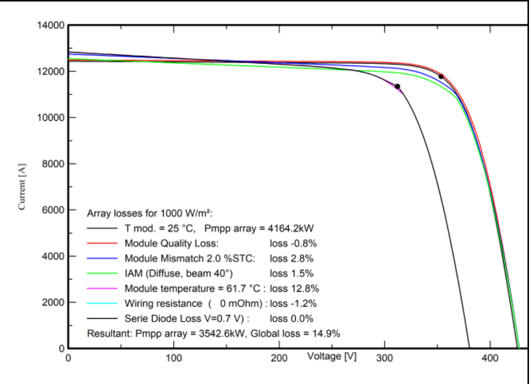

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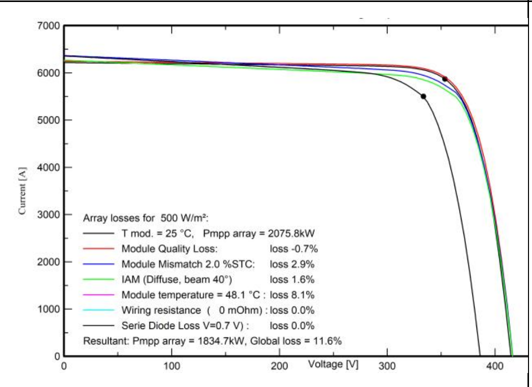

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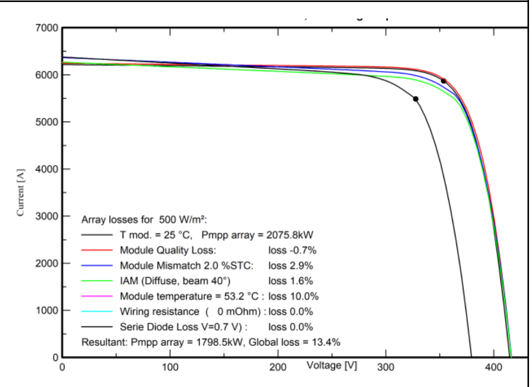

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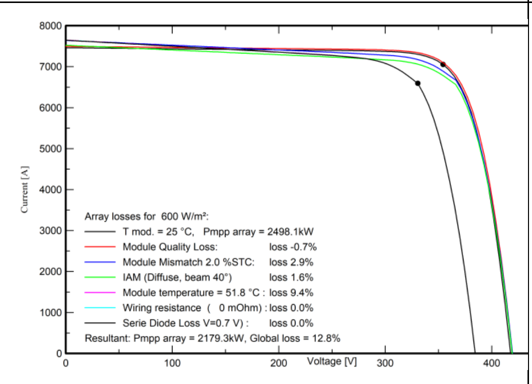

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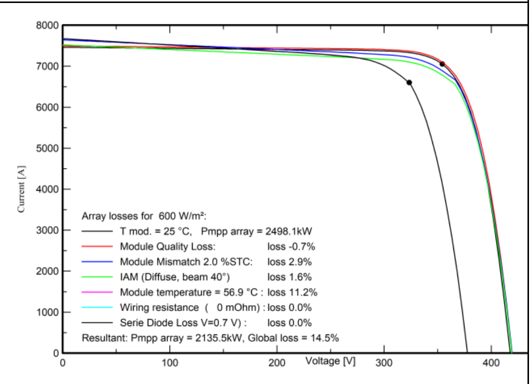

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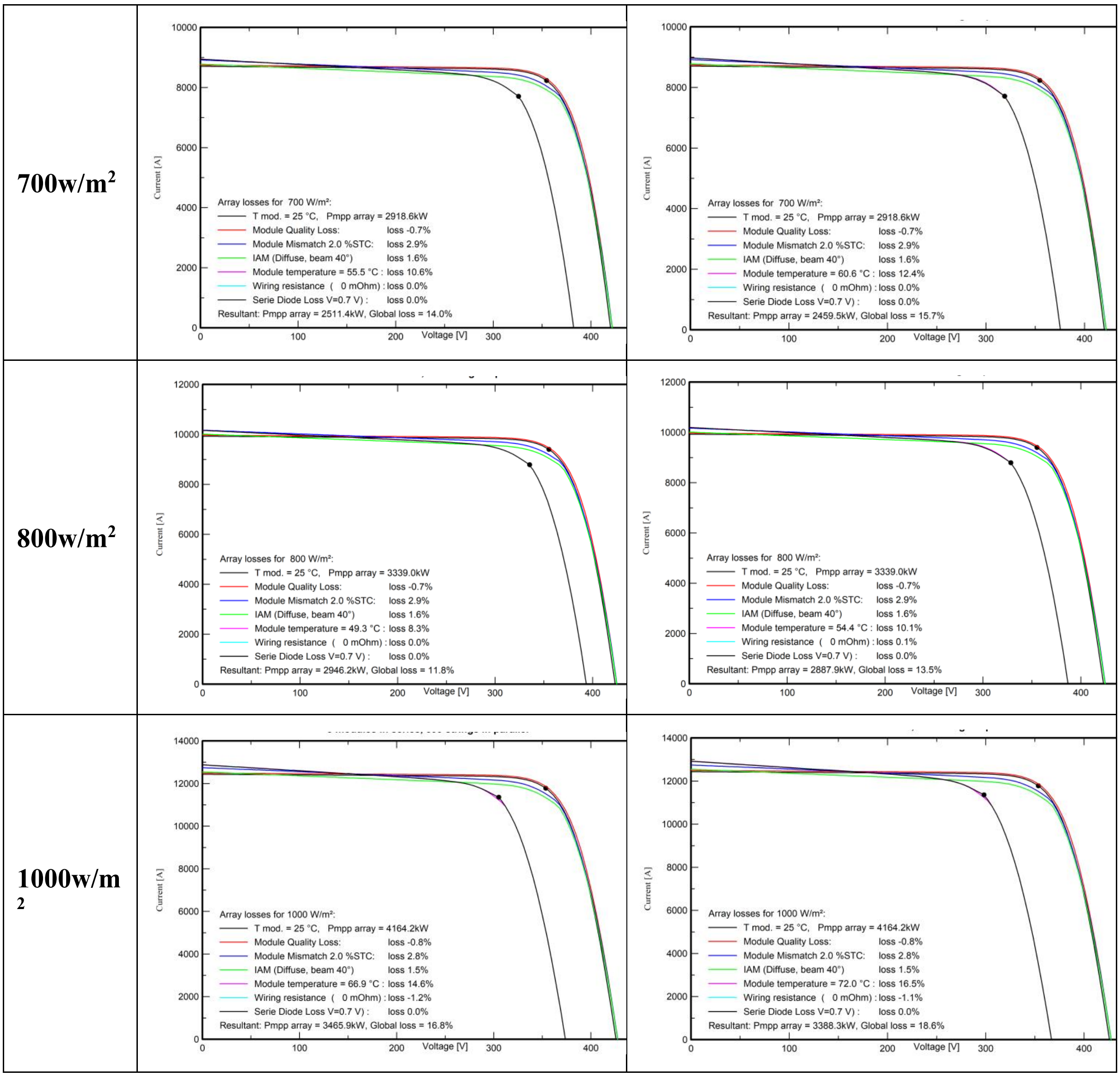

Figure 5: The Case of Investigation at Ambient Temperature

Table 5. Summary of Test Criteria Values

Irradiation(w/m^2)	Ambient Temper (°C)	Pmpp array	Global loss
500	20	1907.3	8.1%
	25	1871.2	9.9%
	30	1834.7	11.6%
	35	1798.5	13.4%
600	20	2265.2	9.30%
	25	2222.4	11.0%
	30	2179.3	12.8%
	35	2135.5	14,5%

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700	20	2613.1	10.5%
	25	2562.6	12.2%
	30	2511.4	14.0%
	35	2459.5	15.7%
800	20	3060.3	8.3%
	25	3003.6	10.0%
	30	2946.2	11.8%
	35	2887.9	13.5%
1000	20	3618.3	13.1%
	25	3542.6	14.9%
	30	3465.9	16.8%
	35	3388.3	18.6%

As shown in Table 5, global losses increased from 8.1% at 20°C to 13.4% at 35°C under 500 W/m² irradiation. A similar trend was observed at higher irradiation levels, with losses reaching 18.6% at 1000 W/m² and 35°C. This confirms the strong influence of ambient temperature on system efficiency.

Previous studies support these findings. For example, Islam et al. (2018) reported that PV efficiency decreases by approximately 0.3–0.5% for every 1°C rise in temperature. The results of this study are consistent with that trend, showing a 12% efficiency decrease between 20°C and 35°C. Such evidence highlights the importance of considering thermal effects, particularly in hot climates such as Iraq. In such contexts, system design should incorporate cooling strategies including improved ventilation, reflective coatings, or optimized module placement to mitigate temperature-induced losses.

CONCLUSION

Photovoltaic energy systems (PVES) have gained growing prominence due to volatile fossil fuel prices and the urgent need to reduce environmental impacts. This global shift toward alternative energy sources, especially solar power, is promising but not without challenges. One of the major limitations is that PV modules rarely operate under standard test conditions (1000 W/m² irradiation and 25°C), especially in countries with extreme climates. Furthermore, sustainability concerns arise from waste generation during manufacturing and replacement of PV modules.

This study highlights the critical role of external factors, particularly ambient temperature and solar irradiation, in determining the performance of PV systems. Specifically, the results emphasize their effect on maximum power point (Pmpp) and global losses, demonstrating the need to optimize design choices to ensure stable energy production. Using PVsyst software, the study verified standard conditions and identified more realistic performance expectations. It was observed that PV efficiency declined by 6% when temperatures exceeded 30°C, underscoring the importance of adapting PV designs to local environmental conditions.

RECOMMENDATIONS

1. When optimizing PV design, it is preferable to maintain a balance between maximum power point (Pmpp) and global losses. Selecting conditions that enhance Pmpp while keeping losses within acceptable limits ensures efficiency levels remain above 6%.
2. Designers should account for 5–10% higher than expected losses to accommodate climatic variability and ensure reliable performance under fluctuating conditions.
3. In some locations, PV system design is based solely on maximum weather conditions. Instead, annual external conditions should also be considered to achieve more accurate system sizing and performance predictions.
4. The analysis indicated that wind velocity significantly influences PV efficiency by enhancing cooling effects. Therefore, system design should include accurate wind assessments when estimating system performance.
5. Determining the optimal incidence angle prior to installation improves solar capture and reduces reflection losses, thereby increasing system output.
6. Investigating the relationship between beam and global radiation ratios allows designers to select operating conditions that maximize efficiency and system reliability.

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