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Thermal Performance Challenges and Mitigation Strategies for Photovoltaic Modules in High-Temperature Climates: A Case Study of Three Libyan Cities in Different Regions

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تحديات الأداء الحراري واستراتيجيات التخفيف للوحدات الكهروضوئية في المناخات مرتفعة الحرارة: دراسة حالة لثلاث مدن ليبية في مناطق مختلفة

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Abstract:
This study provides a comprehensive investigation into the performance of photovoltaic (PV) modules under diverse climatic conditions, emphasizing degradation induced by elevated operating temperatures. Utilizing a MATLAB-based simulation centered on a single-diode equivalent circuit model, the electrical characteristics of a standard crystalline silicon module were analyzed across three geographically distinct Libyan cities: Tripoli (temperate coastal), Sabha (hot-arid), and Kufra (high-altitude subtropical). The model integrates real-world meteorological data, including ambient temperature, solar irradiance, and wind speed, to calculate cell temperature and its impact on electrical parameters. Results quantify a significant efficiency penalty in hotter regions, driven by the module's negative temperature coefficient. This manifested as a marked reduction in maximum power point (MPP) voltage and distinct distortion of the I-V curves in desert climates compared to coastal regions. Specifically, Tripoli maintains the highest operational efficiency (above 17.5%) year-round due to its cooler climate, whereas Kufra, despite superior solar resources, experiences the lowest efficiency due to substantial thermal losses. Furthermore, the study evaluates active cooling as a thermal management intervention. The findings highlight the necessity of region-specific PV system optimization and demonstrate the efficacy of predictive computational modeling for enhancing energy yields in extreme environments.

Keywords: Photovoltaics, MATLAB, Temperature Coefficient, High-Temperature Performance, Thermal Management, Solar Energy Yield.

الملخص
تقدم هذه الدراسة استقصاءً شاملاً لأداء الوحدات الكهروضوئية *(PV)* تحت ظروف مناخية متنوعة، مع التركيز بشكل خاص على تدهور الأداء الناتج عن ارتفاع درجات حرارة التشغيل. باستخدام إطار محاكاة قائم على برنامج *MATLAB* يرتكز على نموذج الدائرة المكافئة ذات الديود الواحد، تم تحليل الخصائص الكهربائية لوحدة سيليكون بلورية قياسية عبر ثلاث مدن ليبية متمايزة جغرافياً: طرابلس (ساحلية معتدلة)،

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سبها (حارة جافة)، والكفرة (شبه استوائية مرتفعة) .يدمج النموذج بيانات الأرصاد الجوية الواقعية، بما في ذلك درجة الحرارة المحيطة والإشعاع الشمسي وسرعة الرياح، لحساب درجة حرارة الخلية وتأثيرها على المعاملات الكهربائية ديناميكياً .وتحدد النتائج كمياً خسارة كبيرة في الكفاءة في المناطق الأكثر حرارة، مدفوعة بمعامل درجة الحرارة السلبي للوحدة .وتجلى ذلك في انخفاض ملحوظ في جهد نقطة الطاقة القصوى *(MPP)* وتشوه واضح في منحنيات *(I-V)* في المناخات الصحراوية مقارنة بالمناطق الساحلية . وبالتحديد، تحافظ طرابلس على أعلى كفاءة تشغيلية (فوق 17.5%) على مدار العام بسبب مناخها الأبرد، بينما تسجل الكفرة، رغم مواردها الشمسية الفائقة، أدنى كفاءة بسبب الخسائر الحرارية الكبيرة .علاوة على ذلك، تقيم الدراسة إمكانات التبريد النشط كتدخل للإدارة الحرارية .وتؤكد النتائج على ضرورة تحسين الأنظمة الكهروضوئية حسب طبيعة كل منطقة، كما تثبت فاعلية النمذجة الحاسوبية التنبؤية في تعزيز عوائد الطاقة في البيئات القاسية.

الكلمات المفتاحية: الخلايا الكهروضوئية، ماتلاب، معامل درجة الحرارة، الأداء في درجات الحرارة العالية، الإدارة الحرارية، إنتاجية الطاقة الشمسية.

1. Introduction

The efficiency of the PV cell is measured by the percentage of solar energy it converts to electricity. This is the most commonly used parameter to gauge how efficient solar cells and panels are. The higher the efficiency of the solar panel, the more sunlight will be converted to energy, and vice versa. Low solar efficiency converts less sunshine to energy.
Designing efficient photovoltaic (PV) cells is challenging due to several factors that limit their performance. A primary limitation is that a quarter of the solar energy reaching Earth cannot be converted into electricity by silicon semiconductors. This is because semiconductors need a minimum amount of energy, known as the band-gap energy, to dislodge an electron from the crystal structure. For silicon, this band-gap energy is 1.12 electron volts. Since sunlight contains photons with a wide range of energies, not all photons have enough energy to displace an electron in a silicon PV cell. Moreover, any photon energy exceeding the band-gap energy converts into heat, which further reduces efficiency because this heat is not utilized for generating electricity

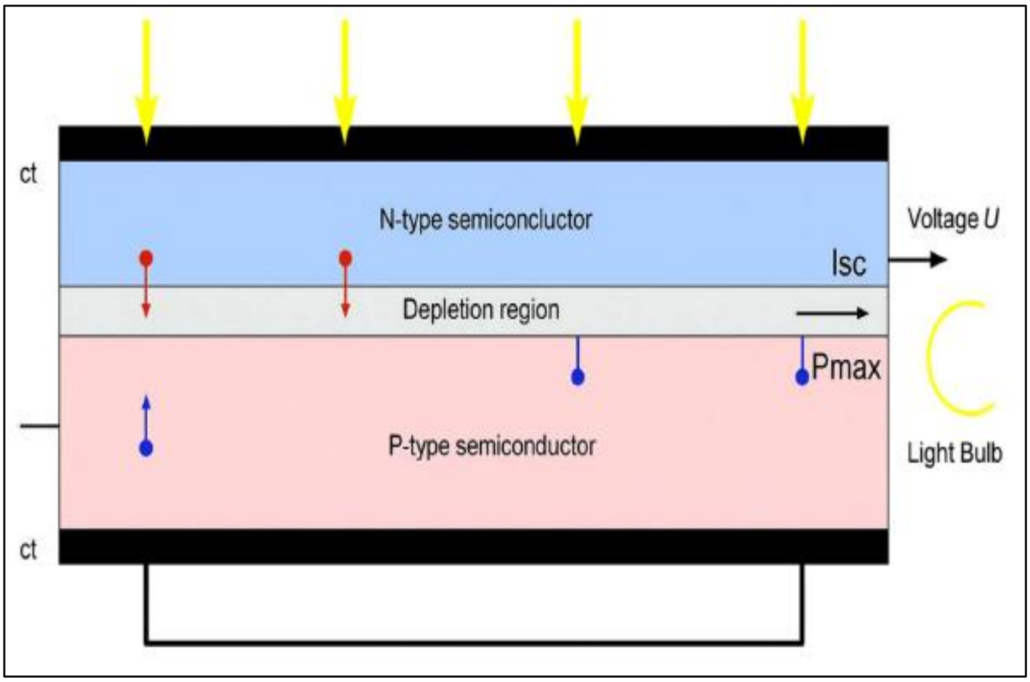

Figure 1. The working principal diagram of photovoltaic panels.

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Additionally, not every electron that becomes available contributes to electricity production Figure 2. Some electrons do not gain enough momentum from the semiconductor's internal voltage to exit the system. These factors lead to a theoretical efficiency limit of about 33% for silicon PV cells.

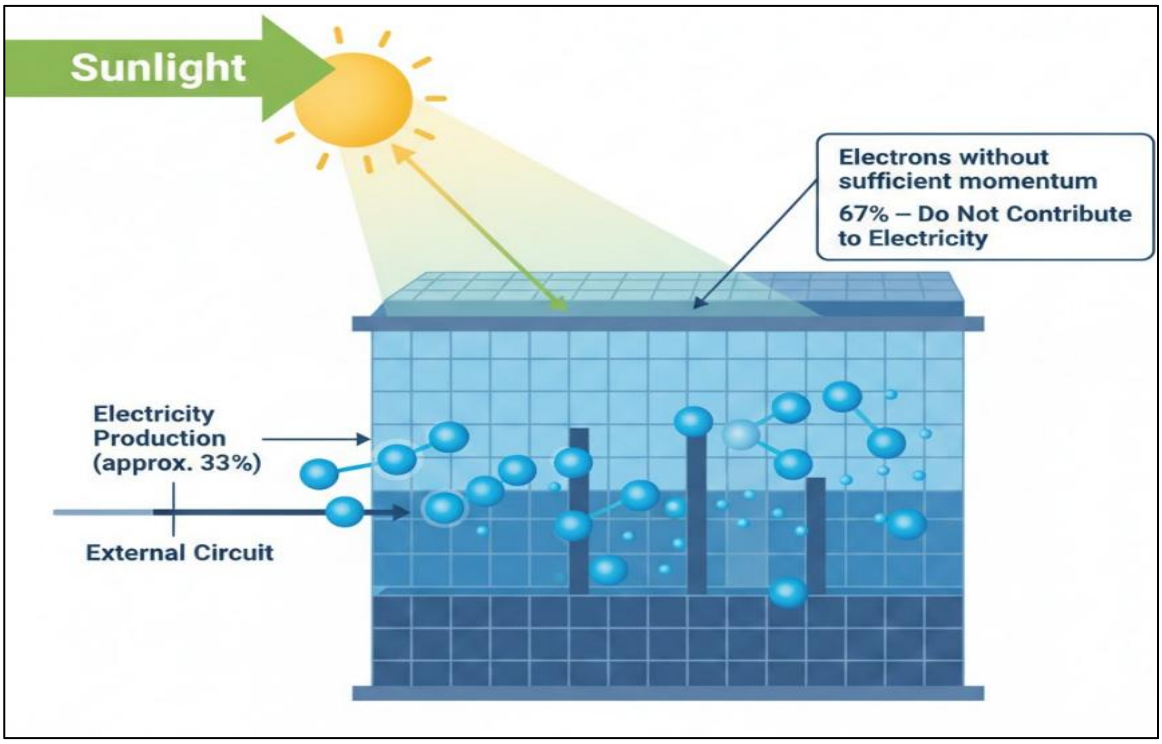

Figure 2. Electrons Without Sufficient Momentum.

To enhance PV cell efficiency, various methods can be employed, each adding to the cost. These methods include improving the semiconductor's purity, using more efficient materials like Gallium Arsenide, adding more layers or p-n junctions to the cell, or concentrating sunlight with concentrated photovoltaics. However, PV cells also experience degradation over time, losing efficiency due to factors like UV exposure and weather cycles.

Photovoltaic (PV) systems are a cornerstone of the global renewable energy transition. However, their efficiency is inherently sensitive to operating temperature, with crystalline silicon (c-Si) modules experiencing a power loss of 0.3% to 0.5% per degree Celsius rise above the Standard Test Condition (STC) of 25°C [3, 12, 15]. In hot climates, module temperatures frequently exceed 65°C, leading to significant efficiency penalties and accelerated long-term degradation. This paper synthesizes current research on the mechanisms of thermal performance loss, including bandgap narrowing, increased recombination rates, and voltage reduction quantified by the temperature coefficient. It reviews the state-of-the-art in thermal management strategies, encompassing passive approaches like radiative cooling and Phase Change Materials (PCMs) [4, 5, 6], active systems [7, 9, 12], and material innovations like Heterojunction (HJT) and TOPCon cells. Furthermore, the analysis highlights critical research gaps, including the need for climate-specific optimization models [1, 16, 17, 21], holistic economic and net-energy assessments of cooling technologies [7, 9], long-term durability studies of advanced materials [6, 27], and validated 3D dynamic models [10, 14, 18]. The paper concludes that a multi-scale approach is essential to unlock the full potential of solar energy in the world's hottest regions.

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The economic viability and energy yield of photovoltaic (PV) installations are fundamentally linked to their long-term performance and degradation rates. While the industry standard projects a linear annual degradation of approximately 0.5% per year for silicon modules as shown in Figure 3, environmental stressors—particularly elevated temperatures—can exacerbate this loss and induce immediate efficiency penalties [12, 15, 27]. In hot and arid regions, which often receive the highest solar irradiance, module operating temperatures can routinely reach 70°C or more. This creates a paradoxical situation where abundant sunlight coincides with suboptimal conversion efficiency due to the inherent negative temperature coefficient of semiconductor materials. This paper aims to provide a comprehensive analysis of the physics underlying thermal efficiency loss, evaluate the array of mitigation strategies from material science to system engineering, and synthesize identified research gaps to guide future work in enhancing PV performance and longevity in high-temperature environments.

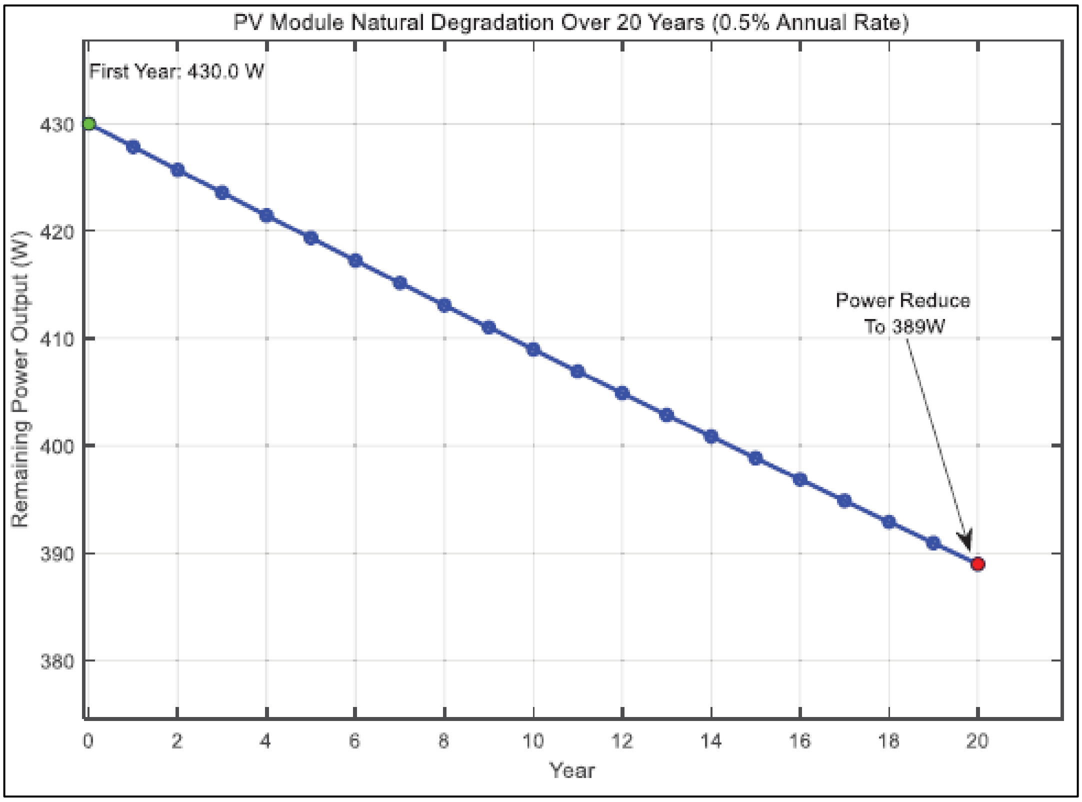

Figure 3. 20-year photovoltaic system efficiency degradation rate under theoretical environment.

1.2. The Physics of Temperature-Induced Efficiency Loss

The efficiency loss in PV cells with increasing temperature is rooted in semiconductor physics and can be described by several key phenomena [3, 11, 15]:

a. **Bandgap Narrowing and Voltage Drop:** As temperature (T) increases, the bandgap energy (E_g) of silicon decreases. This narrowing leads to a significant decrease in Open-Circuit Voltage (V_{oc}), which is the primary driver of power loss [3, 4].
b. **Increased Recombination:** Higher thermal energy accelerates the rate at which photogenerated electron-hole pairs recombine before they can be collected, reducing the available current [3].
c. **Elevated Series Resistance:** Temperature increases the electrical resistance within the cell and interconnection, further lowering the Fill Factor (FF) and power output [3].

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These effects are encapsulated in the **Temperature Coefficient**, a critical performance metric typically ranging from -0.3% to -0.5% per °C for c-Si modules [3, 12, 15]. Consequently, a module operating at 65°C can experience a power reduction of up to 20% compared to its STC rating [3].

1.3. Synergy Between Heat and Long-Term Degradation

High operating temperatures do not only cause immediate power loss but also accelerate long-term degradation mechanisms, threatening module lifespan [27]:

d. **Thermal Cycling Stress:** Diurnal temperature fluctuations cause expansion and contraction, leading to micro-cracks in silicon cells and solder joint fatigue [1,2, 27].
e. **Enhanced Chemical Degradation:** Heat accelerates the browning/discoloration of the Ethylene Vinyl Acetate (EVA) encapsulant due to UV exposure and can exacerbate potential-induced degradation (PID) [1,2, 27].
f. **Material Fatigue:** Sustained high temperatures accelerate the oxidation of contacts and the delamination of layers, compromising the module's structural and electrical integrity [27].

1.4. Strategies for Mitigating Thermal Effects

Mitigation strategies operate at the material, module, and system levels.

1.4.1. Material and Cell Architecture Innovations

a. **Advanced Cell Technologies:** Shift from standard PERC cells to designs with superior temperature coefficients, such as Heterojunction (HJT) and Tunnel Oxide Passivated Contact (TOPCon) cells [4].
b. **Cooling Coatings:** Advanced anti-reflective coatings with high infrared emissivity enable passive radiative cooling, rejecting heat directly to space [4].

1.4.2. Module-Level Thermal Management

a. **Phase Change Materials (PCMs):** Integrated PCMs absorb latent heat during peak insolation, stabilizing module temperature. Studies show electrical efficiency improvements from 13.75% to 17.33% [5]. Enhancements with nanoparticles (e.g., Al_2O_3) improve thermal conductivity [6].
b. **Enhanced Heat Dissipation:** Designs incorporating optimized finned heat sinks improve convective cooling [22].

1.4.3. System-Level Design and Cooling

a. **Passive System Design:** Ensuring adequate ventilation gaps behind roof-mounted panels [3, 16].
b. **Active and Hybrid Cooling:** Active methods (e.g., water spraying) offer high efficiency gains (e.g., 52.62% increase) but incur energy penalties [7, 9, 12]. Hybrid systems combining PCM with active cooling show promising temperature reductions [9]. A critical gap is the absence of standardized activation thresholds and net energy analyses for these systems [7, 12].
c. **Hybrid PV-Thermal (PVT) Systems:** These systems actively cool cells by circulating a fluid, simultaneously producing thermal energy, with coolant flow rate being a key parameter [1, 3].

1.4.4. Operational and Maintenance Strategies

a. **Smart Monitoring:** Using infrared thermography to identify hot spots [File 2].
b. **Soiling Prevention:** Regular cleaning prevents dust accumulation, which insulates panels and increases operating temperature [Files 1,2,4].
c. **Advanced Power Electronics:** Inverters with sophisticated Maximum Power Point Tracking (MPPT) algorithms, such as the Particle Swarm Optimization Memetic Algorithm (PSOMA) that can dynamically optimize tilt angle, show high tracking efficiency [20].

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1.5. Synthesis of Research Gaps and Future Directions

Current literature reveals several critical avenues for future research essential for advancing high-temperature PV performance [Literature_Revie.docx, gap.docx]:

1. **Climate and Application-Specific Optimization:** A lack of tailored performance data and predictive models for extreme climates (e.g., hot-arid, subtropical) and specific applications (e.g., floating PV) [1, 16, 17, 21]. This includes the need for region-specific studies in high-temperature zones and empirical correlations for complex rooftop flow regimes [16].
2. **Holistic Performance and Economic Assessment:** An absence of comprehensive analyses balancing efficiency gains with energy costs and long-term viability. Key gaps include **net energy analyses** for active cooling [7], **economic feasibility assessments** for residential applications [7, 15], and data on the **high cost of advanced materials** like variable PCMs [6].
3. **Advanced Modeling and Experimental Validation:** The need for sophisticated models that move beyond simplified 1D or steady-state assumptions [10, 18] to address 3D heat distribution and dynamic wind patterns [10, 16], coupled with robust **experimental validation of simulation models** using real hardware [8, 27].
4. **Material and System Longevity:** Insufficient investigation into long-term stability, including the **synergistic effects of multiple environmental stressors** [27], stable performance of PCM-integrated designs [6], and the **physical problem of nanoparticle clumping** in nano-enhanced PCMs [6].
5. **Integrated System Design and Macro-Scale Impacts:** Gaps in optimizing system-level integration, such as treating **tilt angle as a dynamic optimization parameter in MPPT** [20], and conducting **comprehensive city-scale analyses** of the microclimatic impacts of large-scale PV deployment [23].

2. The Mathematical Model

This study develops an integrated simulation framework to analyze the performance of photovoltaic (PV) panels under real-world weather conditions, with particular focus on hot climate regions. The methodology combines empirical weather data with physics-based electrical and thermal models to quantify monthly energy yields, efficiency trends, and technology-specific performance degradation due to elevated temperatures.

2.1. Thermal Model

Used to estimate panel temperature based on ambient temperature and solar irradiance.

$$T_{\text{panel}} = T_{\text{ambient}} + G_{\text{solar}} \cdot \left(\frac{\text{NOCT}-20}{800}\right) \quad (1)$$

Where:

a. T_{panel} = Panel temperature (°C)
b. T_{ambient} = Ambient temperature (°C)
c. G_{solar} = Solar irradiance (W/m²)
d. NOCT = Nominal Operating Cell Temperature (°C)

2.2. Electrical Model (I-V and Power Output)

A. Voltage and Current under Real Conditions:

$$V_{\text{inst}} = V_{\text{mp,ref}} \cdot \left[1 + \beta_V \cdot (T_{\text{panel}} - T_{\text{ref}})\right] \quad (2)$$

$$I_{\text{inst}} = I_{\text{mp,ref}} \cdot \left(\frac{G_{\text{solar}}}{1000}\right) \cdot \left[1 + \beta_I \cdot (T_{\text{panel}} - T_{\text{ref}})\right] \quad (3)$$

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Where:

e. $V_{\mathrm{mp,ref}}$, $I_{\mathrm{mp,ref}}$ = Reference maximum power point voltage and current
f. β_V, β_I = Temperature coefficients for voltage and current
g. T_{ref} = Reference temperature (25°C)

B. Power Output:

$$P_{\mathrm{out}} = V_{\mathrm{inst}} \cdot I_{\mathrm{inst}} \quad (4)$$

C. Instantaneous Efficiency:

$$\eta_{\mathrm{inst}} = \frac{P_{\mathrm{out}}}{G_{\mathrm{solar}} \cdot A_{\mathrm{panel}} + \epsilon} \quad (5)$$

Where $A_{\mathrm{panel}} = 1.6\,\mathrm{m}^2$ and ϵ is a small constant to avoid division by zero.

C. I-V Curve Model
For plotting I-V curves under specific monthly conditions:

$$V_a = V_{\mathrm{oc,ref}} \cdot [1 + \beta_V \cdot (T_{\mathrm{panel}} - 25)] \quad (6)$$

$$I_a = I_{\mathrm{sc,ref}} \cdot \left(\frac{G_{\mathrm{scaled}}}{1000}\right) \cdot [1 + \beta_I \cdot (T_{\mathrm{panel}} - 25)] \quad (7)$$

$$I_c = I_a \cdot \left[1 - \left(\frac{V}{V_a}\right)^6\right], \quad I_c \geq 0 \quad (8)$$

Where G_{scaled} = Monthly average GHI × 1.8.

2.3. Technology Comparison Model
A. Power Output for Different Technologies:

$$P_{\mathrm{out}} = P_{\mathrm{max,STC}} \cdot [1 + \alpha \cdot (T - T_{\mathrm{STC}})] \quad (9)$$

Where:

α = Temperature coefficient of power (%/°C)
$T_{\mathrm{STC}} = 25°C$
$P_{\mathrm{max,STC}} = 400$ W

B.Power Output with Irradiance Scaling:

$$P_{\mathrm{out}} = P_{\mathrm{max,STC}} \cdot \left(\frac{G}{G_{\mathrm{STC}}}\right) \cdot [1 + \alpha \cdot (T - T_{\mathrm{STC}})] \quad (10)$$

Where $G_{\mathrm{STC}} = 1000\,\mathrm{W/m}^2$.

This integrated model allows for hourly simulation of panel performance using real weather data, monthly aggregation for trends, and comparative analysis of different PV technologies under high-temperature conditions. Where the inputs parameters are listed in Table 1.

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Table 1. Input Parameters

Symbol	Description	Value / Units
Environmental Inputs (from EPW file)		
T_{ambient}	Ambient dry bulb temperature	°C
G_{solar}	Global horizontal irradiance	W/m²
Month	Month of the year	1–12
Panel Electrical Parameters		
$V_{\text{mp,ref}}$	Max power voltage at STC	36.0 V
$I_{\text{mp,ref}}$	Max power current at STC	8.4 A
$V_{\text{oc,ref}}$	Open-circuit voltage at STC	44.5 V
$I_{\text{sc,ref}}$	Short-circuit current at STC	9.1 A
η_{ref}	Reference efficiency	18%
T_{ref}	Reference temperature	25 °C
NOCT	Nominal operating cell temperature	45 °C
β_V	Temperature coefficient of voltage	–0.0035 /°C
β_I	Temperature coefficient of current	0.0005 /°C
Technology Parameters		
α_{mono}	Mono-Si temperature coefficient	–0.0042 /°C
α_{thin}	Thin-film temperature coefficient	–0.0022 /°C
α_{HJT}	HJT temperature coefficient	–0.00026 /°C
$P_{\text{max,STC}}$	Rated panel power	400 W
G_{STC}	Standard irradiance	1000 W/m²
Simulation Settings		
A_{panel}	Panel area	1.6 m²
G_{levels}	Irradiance scenarios	[400, 800, 1100] W/m²
T_{range}	Temperature range for analysis	25–80 °C

3.Result and Dissections

The solar performance metrics for the three studied locations in Libya are analysis for Tripoli, Sabha, and Kufra.

3.1. Monthly Average Solar Irradiance Analysis

Figure 4 illustrates the Global Horizontal Irradiance (GHI) measured in W/m^{2}across a calendar year.All three locations exhibit a characteristic sinusoidal bell curve, peaking during the summer solstice (June/July) and reaching a nadir in December. The Kufra consistently demonstrates the highest irradiance levels throughout the year, peaking at approximately 335.32 W/m^2 in June. In contrast, Tripoli shows significantly lower winter irradiance, dropping to 120.91 W/m^2 in December, likely due to its higher latitude and increased coastal cloud cover. The higher irradiance in Kufra and Sabha (desert regions) compared to Tripoli (coastal) suggests a higher potential for raw solar energy harvesting in the southern regions of Libya.

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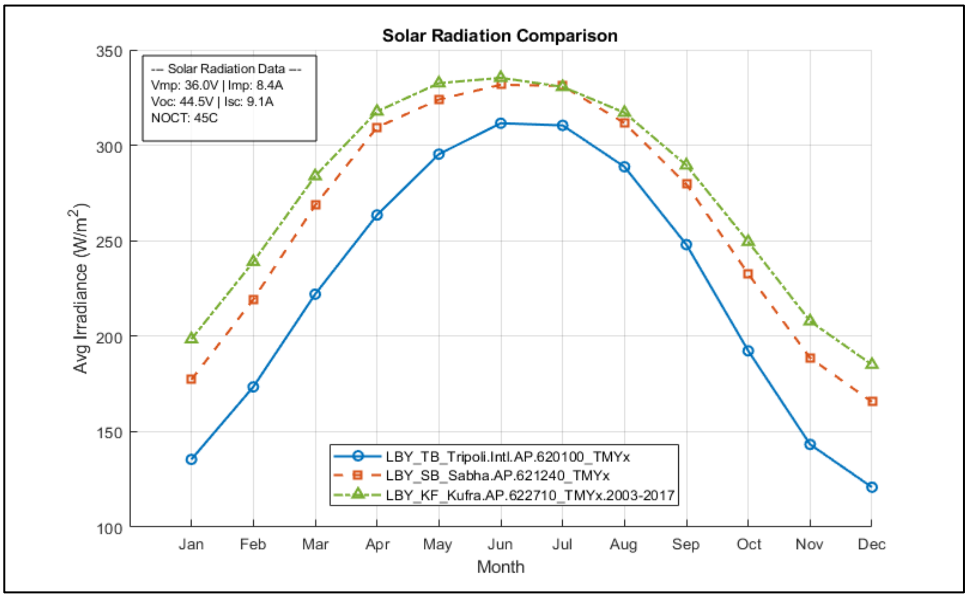

Figure 4: Monthly Average Solar Irradiance Comparison

3.2.Monthly Energy Yield Comparison

Figure 5 depicts the total energy produced by the photovoltaic (PV) system in kilowatt-hours (kWh).The energy yield closely follows the irradiance patterns but is moderated by environmental factors.The peak energy yield is observed in July for Sabha (66.98 kWh) and May for Kufra (67.10 kWh).

The yield curves for Kufra and Sabha show a slight flattening or minor decline between May and July despite high irradiance. This is a classic thermodynamic effect where excessive heat reduces the conversion efficiency of the silicon cells, a phenomenon further explored in the thermal analysis.

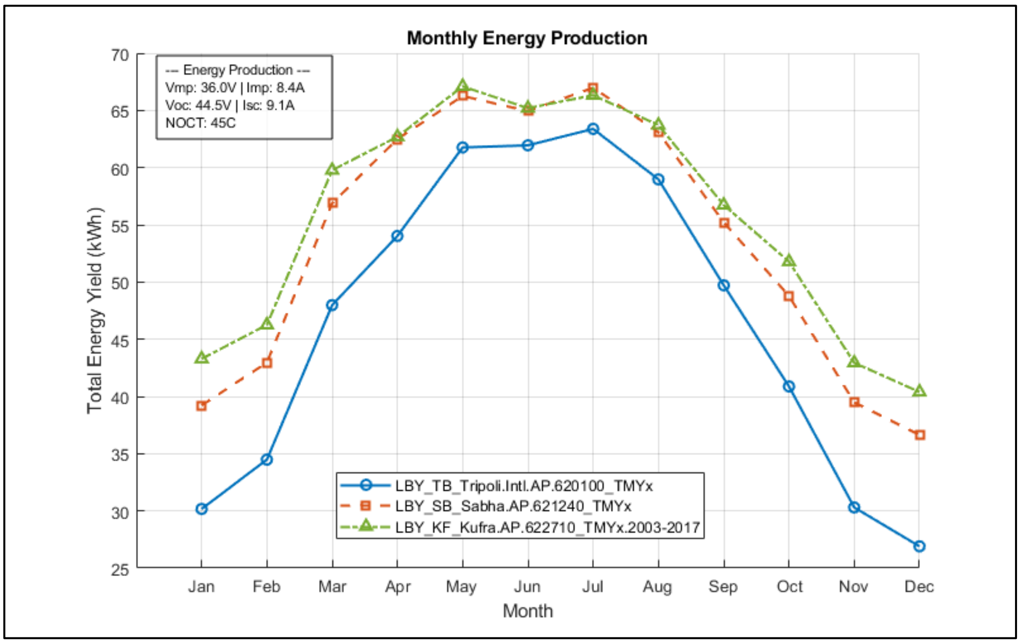

Figure 5: Monthly Energy Yield per Location

3.3. I-V Characteristic Curves (July Peak)

Figure 6 displays the Current-Voltage (I-V) relationship for the three locations during the peak solar month of July.

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The plot shows the relationship between the output current (I) and voltage (V).The short-circuit current (Isc): Kufra and Sabha exhibit higher current plateaus (approximately 5.2 A to 5.5 A) compared to Tripoli (4.5 A) because current is directly proportional to solar irradiance. While the open-circuit voltage (Voc): Interestingly, Tripoli shows a slightly higher voltage threshold before the curve drops to zero. This occurs because V_oc is inversely proportional to temperature; since Tripoli is cooler in July (37.78^circ C panel temp) than Kufra (43.12°C), its voltage degradation is less severe.

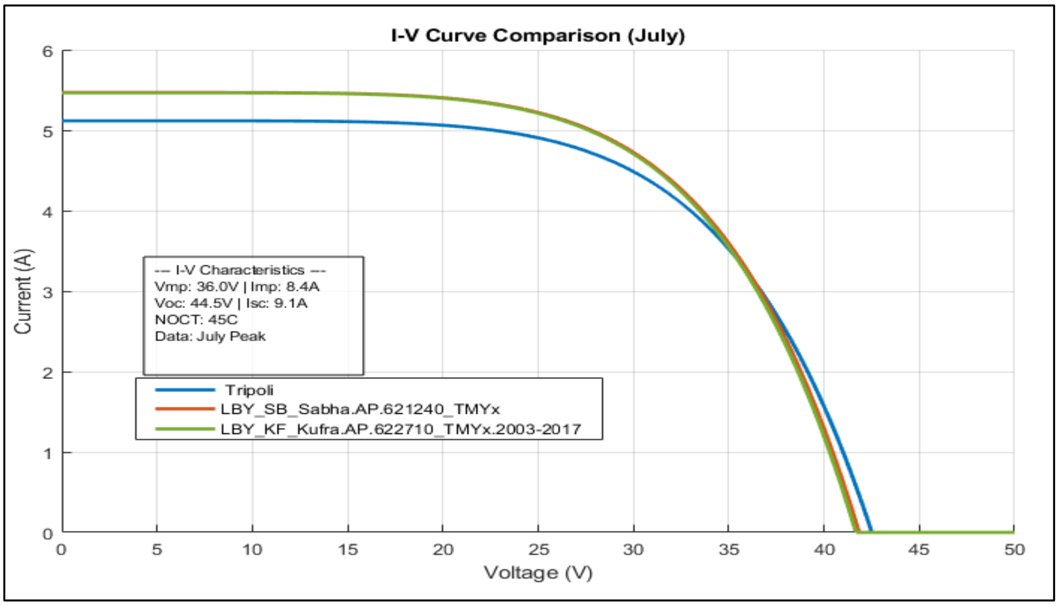

Figure 6. I-V Characteristic Curves for July

3.4. Panel Temperature Analysis

The Thermal Analysis tracks the operational temperature of the PV panels (Tpan) shown in Figure 7. There is a direct correlation between ambient temperature (Tamb) and panel temperature (Tpan).In July, panels in Kufra reach a peak of 43.12°C, while Tripoli remains at a more moderate 37.78°C.These elevated temperatures in southern regions are critical because they lead to "Voltage Compression," which negatively impacts the overall system efficiency despite the abundance of sunlight.

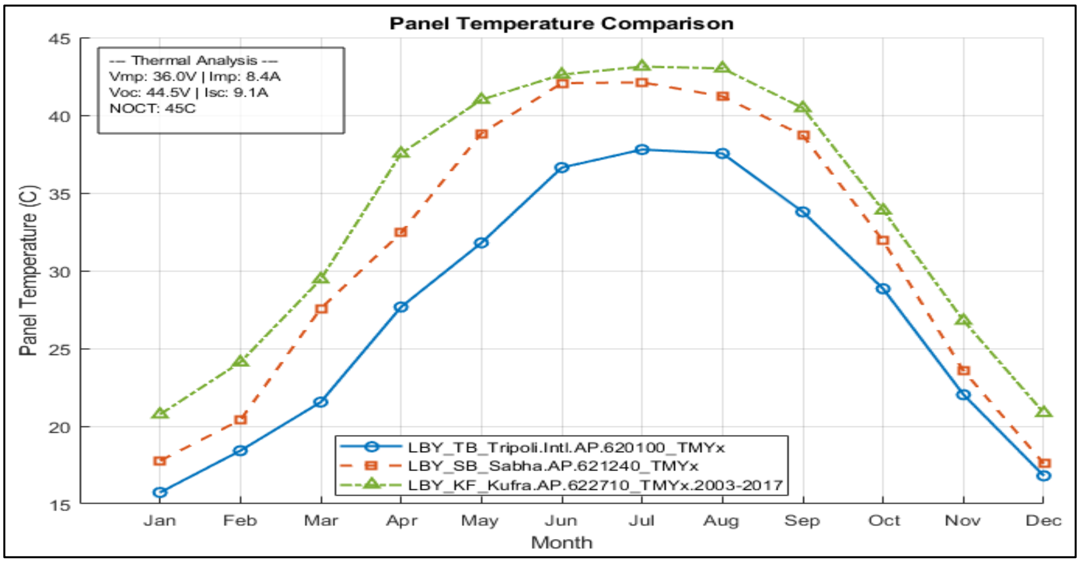

Figure 7: Panel temperature

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3.5. System Efficiency Analysis

Figure 8 illustrates the conversion efficiency percentage (Eff%) of the system throughout the year. The efficiency curves are the inverse of the temperature curves. Efficiency is highest in January (peaking at 18.97% in Tripoli) when the panels are coolest.The efficiency reaches its minimum during the hottest months (July/August).The location performance analysis shows that the panel efficiency in Tripoli maintains the highest efficiency year-round (staying above 17.5%) because its cooler coastal climate allows the PV cells to operate closer to their Standard Test Conditions (STC). Kufra, despite having the most sun, has the lowest operational efficiency due to thermal losses.

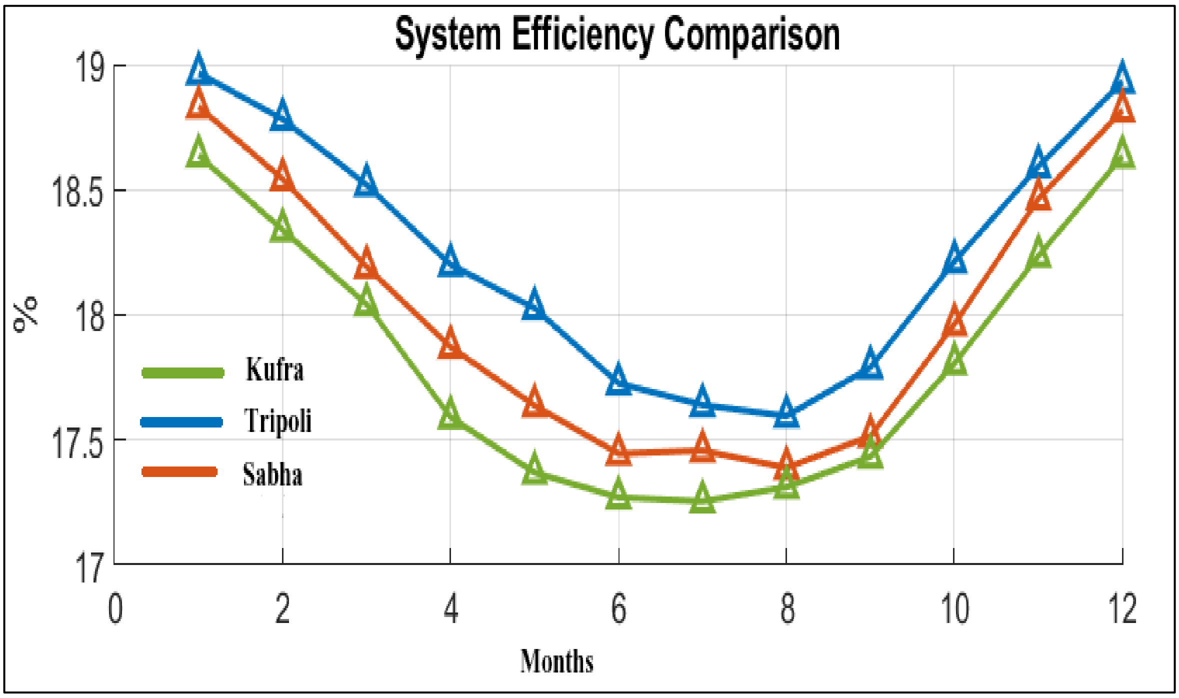

Figure 8: System Efficiency

4. Conclusion

The challenge of temperature-induced efficiency loss remains a critical barrier to optimizing photovoltaic performance, particularly in high-irradiance, high-temperature climates. This research demonstrates that while fundamental semiconductor physics dictates a necessary performance penalty as operating temperatures rise, this impact is manageable through strategic multi-disciplinary interventions. Through comparative analysis of Libyan case studies, it was shown that coastal regions like Tripoli maintain higher operational efficiency (above 17.5%) compared to desert regions like Kufra, despite the latter's superior solar resource, due to significant thermal losses.

The study concludes that a holistic approach—integrating advanced cell architectures such as HJT or TOPCon, innovative passive cooling materials like PCMs, and active thermal managementis essential for maximizing energy harvest. Future research must address current gaps in climate-specific model validation, long-term durability of cooling materials, and comprehensive economic assessments to ensure the deployment of cost-effective and high-performing solar systems in the world's most demanding environments. Addressing these factors is vital for securing the reliability of solar power as a cornerstone of the global sustainable energy transition.

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