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Comparative efficiency assessment of polycrystalline, monocrystalline, and thin-film photovoltaic technologies under Burkina Faso's climatic conditions

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Abstract

This study provides a comparative assessment of the performance of monocrystalline silicon(mono-Si), polycrystalline silicon (poly-Si), and thin-film amorphous silicon (a-Si) photovoltaic modules under Burkina Faso's distinct climatic zones. Using long-term satellite derived irradiation and temperature data from 1994 to 2015, system conversion efficiency, energy yield, and performance ratio are evaluated across semi-arid, arid, humid subhumid, and dry subhumid regions. Results indicate that mono-Si modules achieve the highest energy output in all zones (up to 425.9 kWh.m^2 in arid regions), followed by poly-Si and thin-film modules. However, thin-film technologies exhibit superior performance ratios (up to 0.96), indicating better tolerance to high temperatures. The findings highlight the trade-off between efficiency and environmental resilience, offering data-driven recommendations for PV technology selection in hot and dusty climates of West Africa. This research contributes to optimizing solar energy deployment in regions with high solar potential but challenging environmental conditions.

Keywords: Monocrystalline silicon PV technologies; Polycrystalline silicon PV technologies; Thin-film a–Si PV technologies; Efficiency; Performance Ratio; Climatic regions; Burkina Faso

1. Introduction

Burkina Faso, located in the Sahelian and Sudano-Sahelian climatic zones, faces significant challenges related to electricity access and remains highly dependent on imported fossil fuels [1]. However, the country benefits from high and relatively stable solar irradiance throughout the year, making photovoltaic (PV) energy a key option for sustainable electricity generation [2]. Despite this favorable solar potential, the performance of PV systems is strongly affected by harsh climatic conditions, including high ambient temperatures and seasonal dust events. Elevated temperatures reduce PV module efficiency through increased thermal losses [3, 4], while dust accumulation causes additional power losses, particularly in semi-arid environments [5]. These impacts vary across PV technologies, such as monocrystalline silicon, polycrystalline silicon, and thin-film modules, due to their different thermal and material characteristics [6].

Numerous studies have investigated the performance of different photovoltaic (PV) systems under a variety of system configurations and environmental circumstances. From October 2013 to December 2014, Başoğlu et al. [7] monitored

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three grid–connected solar systems using crystalline silicon (c–Si), multicrystalline silicon (mc–Si), and cadmium telluride (Cd–Te) modules at the Kocaeli University. The system's performance was evaluated using normalized energy yield, performance ratio (PR), mean array efficiency (MAE), and capacity factor. The Cd–Te array had the highest MAE because of its lesser sensitivity to weather variability. The mean PR values for the mc–Si, c–Si, and Cd–Te systems were 83.8%, 82.05%, and 89.76%, respectively. The Cd–Te technology was shown to be the most reliable in Izmit's climatic circumstances, with consistently higher CF values. Ayadi et al. [8] compares the electrical and thermal performance of a bifacial photovoltaic module to three monofacial technologies (half-cut, mono-PERC, and polycrystalline) in Jordanian climatic conditions. Four modules were erected on the University of Jordan's rooftop with a south-facing orientation and a 30° tilt, and monitored for five weeks using a dedicated data gathering system. The results demonstrate that all modules exhibit similar thermal behavior regardless of sensor position, although the bifacial module outperformed the Mono-PERC, Half-cut, and polycrystalline modules by 9.9%, 13.1%, and 24.9%, respectively. Benghanem et al. [9] looks at the performance of polycrystalline and monocrystalline solar modules in an arid, high–irradiance environment, taking into account the impacts of temperature and dust, and extracting module characteristics using the Artificial Hummingbirds algorithm. Under high solar irradiance(>500W.m^{-2}), polycrystalline modules showed lower temperature-induced power losses (≈ 14%) than monocrystalline modules (≈16%). However, under low irradiance circumstances, monocrystalline modules performed better with smaller power degradation (9% versus 21%). Some works [10] had investigated the performance of an 11.04 kWp grid-connected solar system made up of monocrystalline (mc–Si) and polycrystalline (p–Si) silicon modules placed in Kerman, Iran, under identical meteorological circumstances. System and meteorological data were tracked from July 2013 to June 2014 using dedicated acquisition equipment. The p-Si modules outperformed the mc–Si modules, with better yearly average daily final yield (5.38 kWh/kWp/day), performance ratio (82.92%), and capacity factor (23.81%). Nogueira et al. [11] evaluate the performance of a photovoltaic water pumping system powered by monocrystalline and polycrystalline modules installed at the State University of West Paraná (UNIOESTE), Cascavel, Brazil.

The average daily pumped water volumes were 3536.45 L and 4182.55 L for the monocrystalline and polycrystalline systems, respectively, with corresponding module efficiencies of 9.40% and 6.57%. The monocrystalline system achieved an average overall efficiency of 4.27%, with life–cycle costs of 0.104 US \$ m^{-3} and 0.704 US \$ kWh^{-1}, while the polycrystalline system showed a higher global efficiency of 5.00% and costs of 0.096 US \$ mm^{-3} and 1.292 US \$ kWh.m^{-1}. Mirzaei and Mohiabadi [12] monitored outdoors two commercially available photovoltaic modules, monocrystalline and polycrystalline over one year in a semi–arid region of Iran. Power output, specific energy yield, normalized power output, efficiency, and performance ratio were analyzed in relation to local climatic conditions. Although both modules exhibited similar instantaneous responses to solar irradiance, their monthly performance differed due to distinct optical and thermal characteristics. The monocrystalline module showed a decreasing trend in monthly efficiency and performance ratio with increasing ambient temperature, whereas the polycrystalline module exhibited an opposite behavior. Overall, the monocrystalline module achieved higher maximum efficiency and specific energy yield, indicating superior performance at the study site. Bamisile et al. [13] perform the review analyzes six key factors influencing photovoltaic performance: solar irradiance, ambient temperature, atmospheric conditions, terrain effects, extreme weather events, and long-term irradiance variability. Solar irradiance exhibits strong spatial and temporal variability and remains the dominant determinant of PV output, while increasing module temperature reduces efficiency by approximately 0.4-0.5% per °C, constraining performance in hot climates. Atmospheric factors, including clouds, aerosols, pollutants, and dust, can reduce electricity generation by up to 60%, particularly in arid regions, whereas terrain–related effects such as albedo and snow have mixed impacts. Extreme events (e.g., wildfires, hailstorms, and solar eclipses) cause significant but episodic losses, and long–term irradiance changes driven by climate change and air pollution pose emerging challenges for sustaining PV efficiency.

Despite these insights, few studies compare mono–Si, poly–Si, and thin–film directly across Burkina Faso's Sahelian and Sudanian zones, where dust extremes and humidity gradients uniquely interact with technologies [14, 15, 16, 17]. This gap underscores the need for site–specific, long–term field data to inform optimal selections. This research aims to address this knowledge gap by providing a comprehensive comparative analysis of these PV technologies under the specific environmental conditions prevalent in Burkina Faso's distinct climatic regions, thereby offering critical empirical data for strategic energy planning and development [18]. More precisely, this study aims to evaluates the performance of commercially available PV modules (monocrystalline, polycrystalline and thin–film) in Burkina Faso, a country with aride, semi–arid, humid subhumid and dry subhumid environment and significant irradiance potential. We will also offer recommendations for PV system designers in Burkina Faso to select appropriate panels based on local climatic conditions such as irradiation and ambient air temperature. The main objectives of this work are as follows:

- Determine module Conversion efficiency of polycrystalline, monocrystalline and Thin-film PV technologies for each Burkina Faso's climatic regions.

- Study the influence solar irradiation and air temperature on the output power of solar modules with different technologies.
- Investigate the effects of temperature and irradiation on the performance of PV modules of type monocrystalline, polycrystalline and Thin-film.

This paper is structured as follows: Section 1 introduces the photovoltaic technologies under review. Section 2 details the data sources, methodology, and analytical tools employed. Section 3 presents and discusses the results. Finally, Section 4 concludes by summarizing the principal findings and suggesting directions for future research.

2. Material and methods

This section describes the materials, datasets, and methodology used in this investigation. It presents the study region and its climatic zones, details the climate data sources, and outlines the analytical software employed to ensure the accuracy and reproducibility of the results.

2.1. Used PV technologies

Monocrystalline silicon (mono–Si) see Figure 1a panels are renowned for their high efficiency (typically 18–22%) due to uniform crystal structure, but they exhibit greater sensitivity to high temperatures [19]. Polycrystalline silicon (poly–Si) see Figure 1b offers a cost-effective alternative with efficiencies of 15–18%, though it suffers higher temperature coefficients and slightly lower performance under standard conditions [20, 19]. Thin–film photovoltaics provide opportunities for scalable, low-cost, and unconventional solar energy applications [21]. Established thin–film technologies include amorphous silicon (a-Si), cadmium telluride (CdTe), and copper indium gallium selenide (CIGS). Emerging thin-film technologies include perovskites, copper zinc tin sulfide, quantum dots, organic photovoltaics, and dye-sensitized solar cells [21]. Thin–film amorphous silicon (a–Si), with efficiencies of 8–12%, excels in diffuse light and elevated temperatures owing to lower thermal coefficients, making it suitable for hot climates, albeit with lower power density requiring larger areas [16, 19].

2.2. Geographical location and climatic zones

Burkina Faso (9°20’-15°30’ N, 2°- 5°30’ W) presented in Figure 2, a landlocked country in the Sahel region of West Africa, has three main climatic zones: Sahelian, Sudan–Sahelian, and Sudanian [22]. The Sahelian zone features high solar irradiance, extreme heat, low humidity, and heavy dust, while the Sudanian zone has higher rainfall, milder temperatures, and greater humidity [23, 24]. More details, as shown in Figure 3, it is characterized by a major tropical semi-arid climate, strong seasonal variability, and high solar across most of the territory. The country faces rapid population growth and significant rural–urban disparities in infrastructure and energy access. These conditions make Burkina Faso a representative case for evaluating decentralized energy solutions and assessing the performance and feasibility of solar photovoltaic technologies in resource-constrained environments.

a) Monocrystalline silicon (mono–Si)

(b) Polycrystalline silicon (poly–Si)

Figure 1 Mono–Si and Poly –Si solar PV technologies

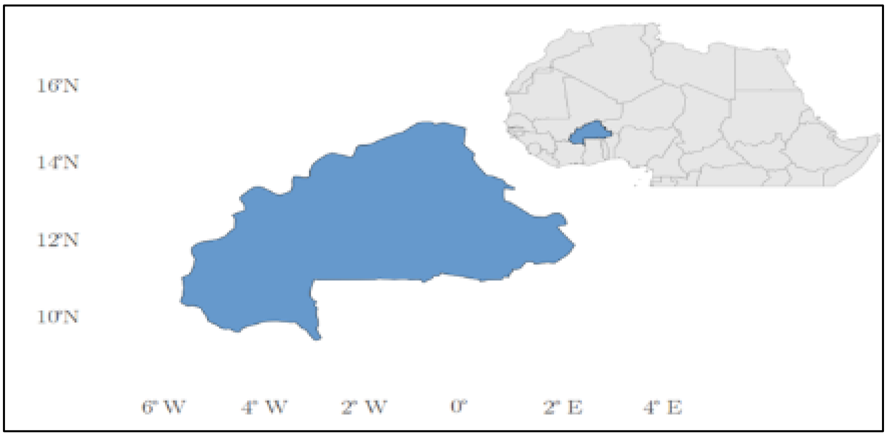

Figure 2 Study area

2.3. Used data

Global irradiation on a tilted surface (GTI) and air ambient temperature (Tair) are climate variables. The World Bank Global Atlas data [25] provide long–term satellite– derived estimates of GTI data for Burkina Faso, covering the period from 1994 to 2015. GTI represents the total beam, diffuse, and ground–reflected solar energy incident on a surface at a particular tilt, which is commonly calculated from global horizontal irradiation. T_{air}, ambient air temperature is the temperature of the surrounding air in a given environment, measured Generally 2m above ground level according to meteorological standards, away from direct heat sources and solar radiation. Tair data are from Climatic Research Unit (CRU TS v. 4.09) [26, 27] where only period from 1994 to 2015 is selected. Table 1 shows area, T_{air} and GTI mean values according to each climate zone presented in figure 3.

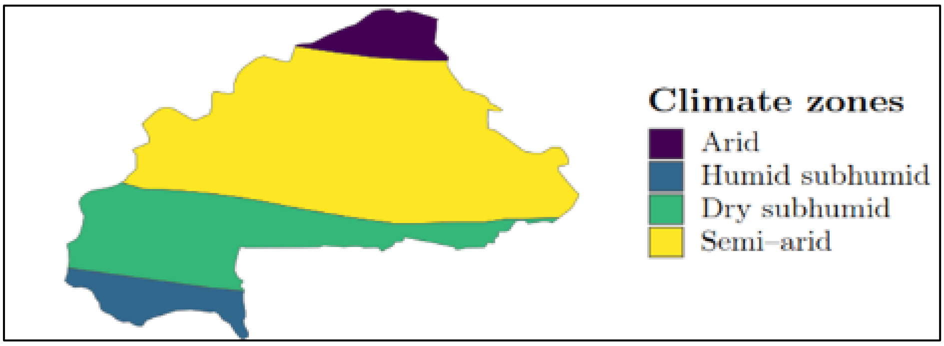

Figure 3 Climatique zones

Table 1 Characteristics of climatic zones

	Area (km²)	**T_{air} (°C)**	**GTI (kWh.year⁻¹.m⁻²))**
Semi–arid	168106.81	28.93	2210.45
Arid	14627.97	29.89	2280.56
Humid subhumid	18721.22	27.75	2063.18
Dry subhumid	72228.85	28.15	2139.75

2.4. Module Conversion efficiency

Photovoltaic technologies Conversion efficiency presented in Equation 1 [28] are determined by temperature coefficient _0, module temperature T_{cell}, and system efficiency linked to Nominal Operating Cell Temperature (NOCT). **Table 2** shows all parameters used in equation 1 and Equation 2 [13] for each considered PV technologies. For the calculations we used average values.

$$\eta_{Sys} = \eta_{ref}[1 - \beta_0(T_{cell} - NOCT)] \quad (1)$$

With T_{cell} defined by

$$T_{cell} = T_{air} + \frac{NOCT-20}{800} GTI \quad (2)$$

In the Equation 1, η_{Sys} and η_{ref} are solar cell efficiencies at cell temperature and NOCT respectively, β_0 represents the efficiency temperature coefficient, and T_{cell} is the cell temperature. Global solar flux is 800 $W.m^{-2}$.

Table 2 Comparison of PV technologies: efficiency, NOCT, and temperature coefficient [13, 29, 30, 31]

	Nominal Efficiency	**NOCT (°C)**	**Temperature Coefficient (%/°C)**
Monocrystalline Si	18–22%	45–48	-0.35 to -0.45
Polycrystalline Si	15–20%	46–50	-0.40 to -0.45
Thin-Film (a-Si)	10–14%	45–55	-0.20 to -0.30

2.5. Energy yield

Solar PV output power evaluation entails quantifying the electrical power generated as a function of plane–of–array irradiance and module temperature. Equation 3 presents a method for output power evaluation

$$E_{Solar}(kWh.year^{-1}.m^{-2}) = GTI.\eta_{Sys} \quad (3)$$

2.6. Performance ratio analysis

To evaluate the performance of PV modules, the Performance ratio (Pr) is determined based on their actual electrical properties, which differ from the Standard Test Conditions (STC) values. (Pr) defined as the ratio of real energy production to product energy at STC, helps quantify losses caused by environmental and operational factors like spectrum, module mismatch, optical reflection, module temperature, and wind speed. Therefore, it indicates the fraction of energy accessible after subtracting energy losses. PV plant location and sun irradiation do not significantly impact (Pr). Equation 4 [12] estimates the yearly (Pr) of each technology.

$$P_r = \frac{\eta_{Sys}}{\eta_{STC}} \quad (4)$$

2.7. Tools for data analysis

The entire treatment, analysis, and visualization were carried out using the R software, a free environment dedicated to statistics, geographic data processing, and visualization. The R programming language [32] (version 4.4.0) was used in this investigation. In addition, Climate Data Operators (CDO) [33] were used to efficiently manipulate gridded climate data in NetCDF format. CDO was utilized for tasks like temporal aggregation, spatial subsetting, regridding, and statistical analysis. The combined usage of R and CDO resulted in robust, transparent, and reproducible data processing operations.

3. Results and discussion

3.1. Module Conversion efficiency

The conversion efficiency of each PV technology, calculated using Equation 1, is summarized in Table 3 and visualized in Figure 4. Monocrystalline modules consistently exhibit the highest efficiency (19%) across all climatic zones, attributed to their superior crystalline structure and higher photon absorption capacity [29]. Polycrystalline modules follow with 16%, while thin-film modules show the lowest efficiency (11–12%), which is consistent with their lower nominal efficiency ranges [21]. Notably, efficiency values remain relatively stable across zones, suggesting that the dominant factor influencing efficiency is technology type rather than climatic variability within Burkina Faso. However, the slight drop in thin-film efficiency in arid zones (11%) may be linked to higher operating temperatures, which affect amorphous silicon more than crystalline technologies [3].

Table 3 Conversion efficiency of PV modules (%)

	Semi–arid	**Arid**	**Humid sub–humid**	**Dry sub–humid**
Monocristallin	0.19	0.19	0.19	0.19
Polycristallin	0.16	0.16	0.16	0.16
Thin-film	0.12	0.11	0.12	0.12

3.2. Output power of solar modules

The annual energy yield per square meter, computed via Equation 3, is presented in Table 4 and Figure 5. As expected, mono-Si modules generate the highest energy output, ranging from 388.97 kWh.m^{-2} in humid sub–humid zones to 425.9 kWh.m^{-2} in arid zones. Poly-Si modules produce 13% less energy, while thin-film modules yield approximately 40% less than mono-Si. These results align with the efficiency rankings and underscore the influence of both irradiance and temperature on energy production. The arid zone, despite having the highest irradiance (2280.56 kWh.m^{-2}), does not proportionally increase energy yield for crystalline modules due to elevated cell temperatures, which reduce efficiency via the temperature coefficient effect [4]. Thin-film modules, with lower temperature coefficients, show more stable output across zones, confirming their suitability for high-temperature environments [16].

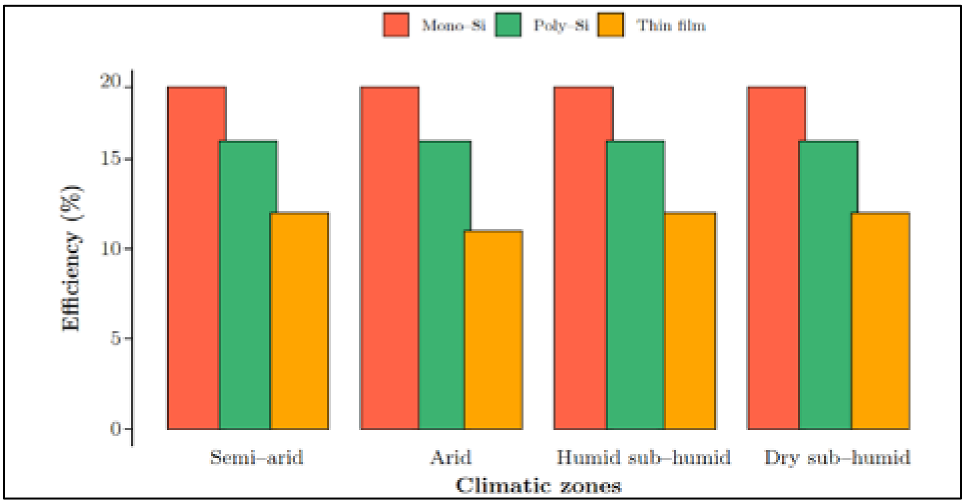

Figure 4 Yearly modules efficiency

Table 4 Output power of solar modules (kWh.m^{-2})

	Semi–arid	**Arid**	**Humid sub–humid**	**Dry sub–humid**
Monocristallin	414.56	425.9	388.97	402.62
Polycristallin	360.62	370.38	338.48	350.31
Thin-film	254.35	261.73	238.18	246.71

3.3. Performance ratio of PV modules

The performance ratio (Pr), calculated using Equation 4, is listed in Table 5 and illustrated in Figure 6. Thin-film modules achieve the highest Pr (0.96) across all zones, indicating lower losses relative to their nominal efficiency under real operating conditions. Mono-Si and poly-Si modules exhibit slightly lower Pr values (0.93–0.94), reflecting their higher sensitivity to temperature and irradiance variations [12]. The consistency of Pr across climatic zones suggests that system–level losses such as optical and mismatch losses are relatively uniform, but temperature-induced efficiency drops remain a significant factor for crystalline technologies. These findings support previous studies indicating that thin-film technologies are more robust under variable and harsh climatic conditions [17, 9].

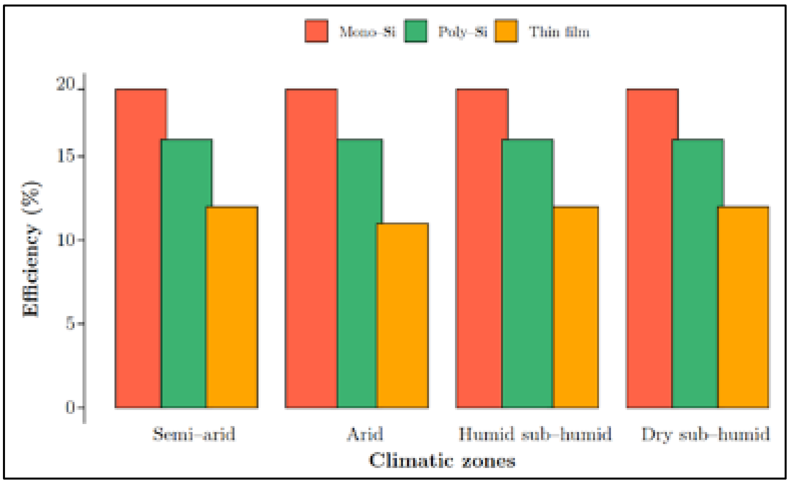

Figure 5 Yearly total energy generated

Table 5 Performance ratio of PV modules

	Semi–arid	Arid	Humid sub–humid	Dry sub–humid
Monocristallin	0.94	0.93	0.94	0.94
Polycristallin	0.93	0.93	0.94	0.94
Thin-film	0.96	0.96	0.96	0.96

3.4. Deficiency of this research paper

While this study provides valuable insights into PV performance under Burkina Faso's climatic conditions, it has several limitations. Only temperature and solar irradiation are considered, neglecting other influential factors such as wind speed, humidity, dust accumulation, and cloud cover, which can significantly impact PV output [13]. Dust deposition, in particular, is a critical factor in semi-arid regions and can reduce efficiency independently of temperature [5]. Furthermore, system–level losses including inverter efficiency, wiring losses, and shading are not accounted for, potentially leading to overestimated energy yields. Future work should incorporate these variables through field measurements and long–term monitoring to enhance the accuracy of performance predictions.

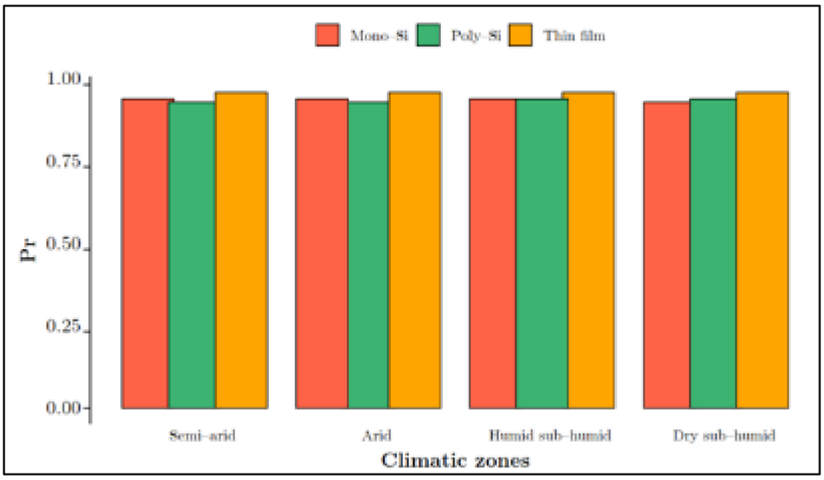

Figure 6 Yearly performance ratio of each technology

4. Conclusion

This study provides a data-driven comparative assessment of monocrystalline, polycrystalline, and thin-film photovoltaic technologies under Burkina Faso's distinct climatic conditions. The results indicate that monocrystalline modules achieve the highest annual energy yield, reaching 425.9 kWh.m^{-2} in arid zones, followed by polycrystalline (370.38 kWh.m^{-2}) and thin–film modules (261.73 kWh.m^{-2}). Despite their lower efficiency (13%), thin–film technologies exhibit the highest performance ratio (0.96), demonstrating superior resilience to high–temperature conditions prevalent in Burkina Faso. Monocrystalline modules maintain a stable efficiency of 19% across all zones, while polycrystalline modules show 16% efficiency, both with performance ratios of 0.93 – 0.94.

The findings underscore a critical trade–off: monocrystalline modules maximize energy output where space is constrained, while thin–film modules offer greater reliability under thermal stress. For Burkina Faso's Sahelian and Sudanian zones characterized by high irradiance (2063-2281 kWh.m^{-2}. year^{-1}) and elevated ambient temperatures (27.75-29.89°C) thin-film PV emerges as a robust option for long–term deployment in rural and off–grid applications.

Future research should incorporate field measurements of dust accumulation, humidity effects, and system–level losses to refine these predictions. This study provides actionable insights for policymakers, energy planners, and PV system designers aiming to optimize solar energy deployment in West Africa's hot and dusty climates.

Compliance with ethical standards

Disclosure of Conflict of interest

The authors declare no conflict of interest to be disclosed.

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