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Simulation-Based Comparative Assessment of Monocrystalline Silicon and CdTe Photovoltaic Systems Under Hot-Arid Conditions: Performance and Techno-Economic Scenarios

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Abstract: Photovoltaic technology selection in hot-arid regions cannot be based solely on Standard Test Condition (STC) efficiency because elevated temperature and soiling can substantially alter annual yield and project economics. Moreover, a simulation-based scenario comparison was performed for 10 kWp monocrystalline-silicon (Mono-Si) and 10 kWp CdTe thin-film systems. PVsyst 7.4 modeled annual energy and losses, MATLAB/Simulink examined temperature-dependent electrical behavior, and LCOE scenarios assessed economic performance. Under the baseline assumptions, CdTe produced 17.96 MWh/year versus 17.52 MWh/year for Mono-Si, with performance ratios of 79.3% and 77.4%. Temperature-related losses were 8.4% and 11.8%, respectively, and baseline LCOE values were approximately 42 and 45 USD/MWh. Within the modeled assumptions, CdTe shows a modest hot-climate advantage despite lower STC efficiency.

Keywords: Photovoltaic performance, Monocrystalline silicon, Thin-film CdTe, High-temperature regions, Temperature coefficient, Degradation rate, LCOE.

1. Introduction

Over recent decades, the accelerating global demand for clean and environmentally sustainable energy, coupled with the progressive depletion of conventional energy resources and the severe ecological consequences of greenhouse-gas and pollutant emissions, has intensified the transition toward low-carbon energy systems [1,2]. Consequently, governments worldwide are seeking to diversify their energy portfolios by deploying renewable technologies capable of providing secure, sustainable, and carbon-free electricity. Among these technologies, solar photovoltaic (PV) systems have emerged as a particularly attractive option because of their modularity, design flexibility, scalability, broad resource availability, relatively low operation and maintenance requirements, and negligible direct emissions during electricity generation [3,4]. By the end of 2023, cumulative global installed PV capacity had exceeded 1,600 GW, positioning solar PV as the largest component of installed renewable-energy capacity worldwide, according to the International Renewable Energy Agency (IRENA). The Middle East and North Africa region is especially well positioned for continued PV expansion because of its exceptional solar-resource potential, with direct normal irradiation frequently exceeding 2,000 kWh/m²/year [5-7].

PV solar panels have ratings under conditions of STC (Standard test condition: 25 °C, 1000 Wm²) in order to compare panels' features in their standard parameters; however, the operating temperature of PV cells in desert climates usually varies from 45°C to 50°C in direct sunlight, which causes serious problems as module efficiencies to decline [8]. Under such conditions, the Voc (open-circuit voltage) of the cell usually drops, and so the series resistance of the cells becomes higher; the durability and lifespan of components decline; LCOE is elevated because high temperature also increases the process of module degradation and reduces the lifetime of PV components. There are two leading market- share photovoltaics (PV) types: conventional silicon-based cells (Mono-Si, Multi-Si) and Thin-film cells (CdTe, a-Si) [9].

Mono-Si-based cells have very wide acceptance mainly due to their initial High efficiencies (around 20-22%) [10]. A low negative Temperature coefficient of -0.3%/°C (which means efficiency reduces as the temperature grows) makes them strongly exposed to thermal impacts. In comparison, thin cells have lower efficiencies when they perform within standard testing conditions, compared to Mono-Si cells; however, they're much more efficient at higher temperatures and have a slower degradation rate in high-temperature exposure, based on a low negative temperature coefficient of about -0.25%/°C [11].

Numerous studies [12-15] were performed to research the PV performance in various environmental and climatic regions around the globe; but only a very low proportion performed controlled comparisons of monocrystalline silicon (Mono-Si) versus thin-film technology for long-duration testing under highly contaminated (dust/sand) and extremely high-temperature conditions found in desert environments. More existing work [16-18] concentrated on STC conditions, while ignoring the combination factors of severe thermal stress and dust deposition/degradation on technology over long time scale both on the technical, as well as, the economic basis.

This study investigates performance the of monocrystalline Silicon and thin film photovoltaic cells PV technologies on a field with rigorous experimental and modelling conditions in the environment conditions found in hot and arid areas such as desert, particularly it assess the influence of ambient temperature on thermal dependent performance for two different types of PV modules through integrated of experimental data, simulation tool, evaluates also the behavior of PV module's Degradation, so it analysis both techno-economic feasibility of photovoltaic electricity production for PV technology in hot & dry regions through the use of the 'LCOE' (Lovelized cost of electricity) under conditions of pollution, degraded environment, and maintenance, to determine a solution or guidelines for increasing the life, efficiency and usage of photovoltaics' in the desert region. In addition, this study makes the assumption that although thin-film PV modules often have lower efficiencies under STC than monocrystalline PV modules, they may produce higher cumulative electricity output and greater economic benefit under desert operating conditions due to better thermal performance and low degradation rates.

2. Literature review

Basic concepts are a set of scientific terms and concepts specific to the study, enabling a particular understanding of the research procedures, especially for specialists. Among the most important of these concepts are:

- Photovoltaic (PV) Technology

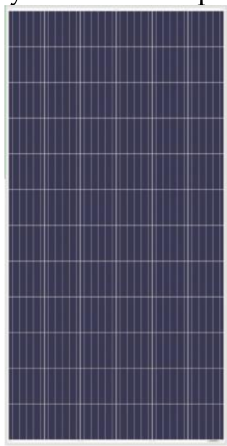
Photovoltaic (PV) technology is one of the fastest growing renewable energy technologies and is a key enabler of the global transition to clean and sustainable energy systems [19]. Photovoltaic cells are designed to convert solar radiation into electricity through a phenomenon called the photovoltaic effect, where a semiconductor cell produces electrical current when excited by the sun's rays [20]. Monocrystalline silicon (Mono-Si) modules are characterized by their efficiency and long lifespan among the commercially available PV technologies, while the thin film technologies like CdTe, CIGS and amorphous silicon (a-Si) are known for their excellent thermal stability and lower operating temperature performance. Selection of appropriate PV technology is crucial and dependent on various technical and environmental factors such as the solar insolation levels, ambient temperature, installation specifics and long-term maintenance considerations [21].

Figure 1 shows a visual comparison of several types of solar panels, including flexible panels, crystalline panels, and thin-film panels. The image highlights differences in design, structure, and flexibility, noting that some thin-film technologies may offer better thermal performance but may have a shorter lifespan compared to traditional crystalline panels.

(a) Flexible solar panel

(b) Monocrystalline solar panel

(c) Thin-film (amorphous silicon solar panel)



(d) polycrystalline solar panel

Figure 1. Visual Comparison of Several Solar Panel Types.

Flexible solar panel

- Temperature effects on the performance of photovoltaic modules

Among all the environmental parameters, temperature is considered one of the most significant factors for PV module performance. As the operating temperature of PV modules rises, the efficiency of PV semiconductor devices reduces due to the decreased open-circuit voltage and increased recombination of carriers [22,23]. As a result, the operating efficiency of photovoltaic modules under field conditions is much lower than their theoretical efficiency rated at Standard Test Conditions (STC). This temperature-induced degradation will vary with different technologies depending on the temperature coefficient, and this factor is important in PV module selection for high-temperature climatic conditions [24-26].

- Degradation of photovoltaic modules

Degradation of photovoltaic modules is defined as any gradual reduction in output electrical power over the useful life of the photovoltaic system, and this is due to constant exposure to various environmental conditions such as UV irradiation, temperature cycles, humidity, dust and mechanical stresses applied to the PV modules [27,28]. Environmental stressors on the PV modules are responsible for aging of materials, discoloration of the encapsulant, cracking of the cell, corrosion and electrical losses, leading to a decrease in annual energy yield of the PV systems. Since degradation of photovoltaic modules affects their Reliability and lifetime energy yield, determination of the long-term degradation rates has become an integral performance parameter in comparing various PV technologies [29,30].

- Thin film and monocrystalline photovoltaic technologies

Monocrystalline silicon modules provide a higher conversion efficiency than thin film technologies and remain a predominant type in the commercial PV industry based on their long-standing reliability and high efficiency performance under Standard Test Conditions; however, their performance has been known to significantly decrease with increasing operating temperature [31,32]. The use of thin-film technologies provides a lower nominal efficiency in comparison to monocrystalline silicon but is considered to perform better at high-temperature operating conditions due to its better thermal resistance and low temperature coefficients, and enhanced thermal performance under desert environments. A comparison of both technologies should not only focus on the instantaneous performance but also on their long-term energy yield and operating life [33,34].

- Levelized cost of energy (LCOE)

The Levelized Cost of Energy (LCOE) has been widely used as one of the standard economic indicators to judge the viability of a renewable energy project [35,36]. LCOE quantifies the levelized cost over its lifetime on a per-unit output of electricity of a generating system, considering the entire life cycle, from capital construction, financing, operations and maintenance, system replacement, degradation, and energy generated by the system [37,38]. LCOE provides a clear method to compare different PV technologies based on their technical performance and economics [39,40].

- Photovoltaic system simulation

One of the most efficient ways to approximate the performance of photovoltaic modules under any climatic and operational condition is to carry out an extensive simulation study. Several software models exist, such as PVsyst, MAT LAB / SIMULINK, and various other programs that help researchers determine the energy yield, thermal performance and losses, system performance, degradation characteristics, etc., prior to and during larger installations [41,42]. A comparison with actual field measurements can be done to provide an accurate simulated value which can guide towards optimizing PV system design and deployment, and technology evaluation for best possible lifetime energy gain [43-45].

- Techno-economic assessment of photovoltaic systems

The assessment of the PV systems needs to be a joint engineering performance and economic study, in order to evaluate the viability of different PV technologies [46,47]. It has to include the electrical energy produced, efficiency, degradation of each technology, need for operation and maintenance, electrical performance under different conditions and cost, and finally the energy produced over lifetime for appropriate comparison, instead of looking only into the electrical parameters obtained during lab tests, especially in hot and dry regions [48-50].

3. Materials and Methods

This study adopts a simulation-based comparative methodology to evaluate monocrystalline-silicon (Mono-Si) and cadmium-telluride (CdTe) thin-film photovoltaic systems under representative hot-arid conditions. The analysis integrates annual performance modeling in PVsyst 7.4, temperature-dependent electrical analysis in MATLAB/Simulink, and techno-economic scenario assessment using LCOE. No field measurements are presented as empirical validation. All software-derived or assumed quantities are therefore identified as simulated or scenario values, and the findings are interpreted as comparative scenarios rather than experimental technology-level inference.

A. Simulation Framework and Scope

The framework comprises definition of a representative hot-arid climate scenario, specification of equal-capacity Mono-Si and CdTe systems, PVsyst annual-yield and loss simulation, MATLAB/Simulink thermal-electrical analysis, LCOE assessment, and sensitivity analysis. Equal nominal capacity does not imply equal module area or balance-of-system cost; consequently, economic outputs are treated as scenario results. Figure 2 represents methodology.

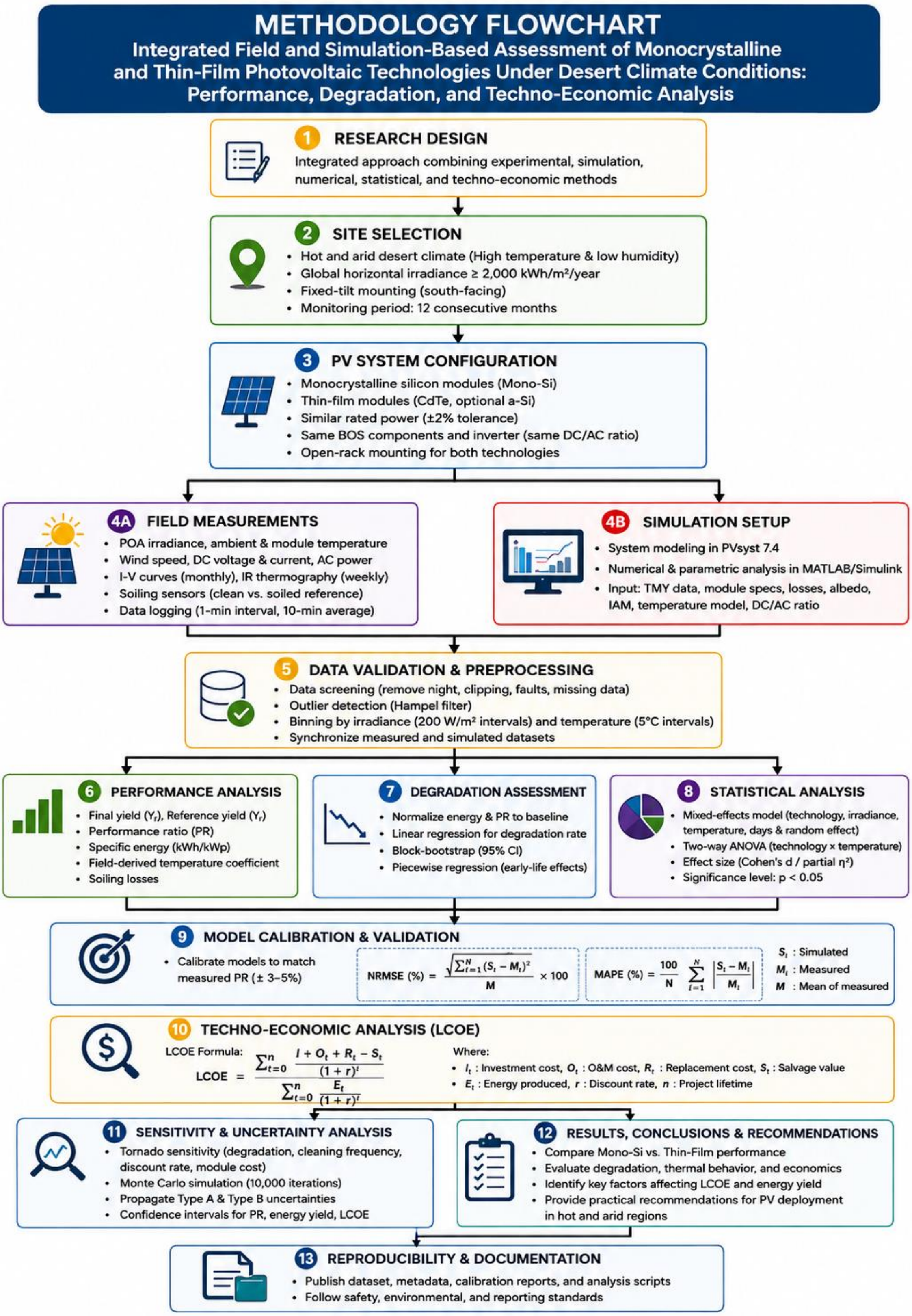


Figure 2. Methodology.

B. *Simulation Procedures and Model Inputs*

This section outlines the procedures for the applied study.

- *Selection of study sites and monitoring period*

A representative hot-arid Libyan climate scenario was used as the environmental basis of the simulations. Solar resource, ambient temperature, wind and related meteorological quantities were treated as model inputs rather than measured observations. The simulation horizon was one year to capture seasonal variation. The study therefore does not claim two-site field monitoring.

- *Photovoltaic Test Set-Ups*

Two technology scenarios were modeled at equal nominal DC capacity: a monocrystalline-silicon (Mono-Si) system and a cadmium-telluride (CdTe) thin-film system. The comparison is limited to the modeled parameter sets and is not generalized to every commercial Mono-Si or thin-film product.

  - Both PV technologies will share the same maximum power point tracker in the same inverter and will be adjusted to the same DC/AC ratio.
  - Both technologies will be arranged to be mounted in an open rack configuration in order to offer similar convective cooling.

- *Instrumentation and data acquisition*

The principal model inputs comprised plane-of-array irradiance, ambient temperature, module-temperature behavior, wind speed, DC electrical characteristics, inverter efficiency and soiling assumptions. These quantities were software/model inputs; no pyranometer, RTD, anemometer, I-V tracer, infrared-camera or field data-acquisition measurements are claimed.

The ambient temperature will be measured on a sheltered temperature sensor, approximately 2 meters above the surface of the soil and wind speed will be measured with a cup anemometer. An alternating current AC inverter power and a DC voltage and current string measurement shall be recorded; monthly current-voltage curve measurements at panel string level, by means of an I-V tracer. Infrared photography shall be used once a week, approximately around noon, to diagnose hotspots in the array. Soiling shall be quantified with two parallel but unequally polluted irradiance sensors or with one clean and one naturally soiling reference module. Data will be logged at one-minute intervals, which will be time-averaged into 10-minute groups with a GPS-synchronized data-acquisition system. At least 95% of data completeness must be reached.

- *Data screening and pre-processing*

Input series were harmonized to consistent units and time bases before simulation. Nighttime periods were excluded from PV-production analysis and irradiance/temperature conditions were treated consistently across technologies. No empirical missing-data imputation or sensor-quality screening is claimed.

  - Intervals of irradiance level between 0 and max irradiance level in steps of e.g.
  - 200 W/m, and of temperature level in step of e.g. 5C have to be defined.

- *Performance Indicators*

The performance of each photovoltaic technology will be evaluated using final yield, reference yield, performance ratio, specific energy production, field-derived temperature coefficient, and soiling loss.

The final yield will be calculated as:

$$Y_f = \frac{E_{AC}}{P_{STC}} \tag{1}$$

where E_{AC} is the AC energy generated during the assessment period and P_{STC} is the rated DC capacity under Standard Test Conditions. The reference yield will be calculated as:

$$Y_r = \frac{H_{POA}}{G_{STC}} \tag{2}$$

where H_{POA} is the plane-of-array solar irradiation and $G_{STC} = 1$ kW/m^2.
The performance ratio will be determined as:

$$PR = \frac{Y_f}{Y_r} \times 100 \tag{3}$$

The field-derived power temperature coefficient will be estimated by regressing normalized maximum power against module temperature under high-irradiance conditions, preferably when plane-of-array irradiance is at least 800 W/m²:

$$\frac{P_{\max}}{P_{STC}} = \alpha + \beta_P (T_{\text{cell}} - 25) + \varepsilon \tag{4}$$

where β_P represents the field-derived power temperature coefficient.
Soiling loss will be calculated as:

$$L_s = 1 - \frac{G_{\text{soiled}}}{G_{\text{clean}}} \tag{5}$$

where G_{soiled} and G_{clean} represent irradiance measured by the naturally soiled and cleaned reference sensors, respectively.

- *Degradation Assessment*

Long-term degradation was not estimated from a one-year field record. Instead, degradation was treated as an exogenous techno-economic scenario parameter. The values 0.61%/year for Mono-Si and 0.46%/year for CdTe are baseline assumptions used for lifetime-energy and LCOE calculations, not measured degradation rates. Their influence is examined through sensitivity analysis. No experimentally established annual degradation superiority is claimed. Multi-year, time-matched field monitoring would be required for technology-specific degradation estimates with seasonal correction and uncertainty.

- *Numerical Simulation and Model Validation*

PVsyst 7.4 was used to simulate annual PV production and principal loss mechanisms. MATLAB/Simulink was used to examine temperature-dependent electrical behavior and selected dynamic responses. Agreement between the two platforms is interpreted only as a cross-model consistency check, not as validation against experimental measurements.

$$NRMSE = \frac{\sqrt{\frac{1}{n}\sum_{i=1}^{n}(S_i - M_i)^2}}{\bar{M}} \times 100 \tag{7}$$

$$MAPE = \frac{100}{n}\sum_{i=1}^{n}\left|\frac{S_i - M_i}{M_i}\right| \tag{8}$$

$$MBE = \frac{1}{n}\sum_{i=1}^{n}(S_i - M_i) \tag{9}$$

where S_i and M_i denote simulated and measured values, respectively. The validated models will subsequently be used to evaluate alternative cleaning frequencies, airflow conditions, DC/AC ratios, and spectral or environmental scenarios.

- *Techno-Economic Analysis*

The economic performance of the two photovoltaic technologies will be evaluated using the Levelized Cost of Energy:

$$LCOE = \frac{\sum_{t=0}^{N}\frac{I_t + O_t + R_t - S_t}{(1+r)^t}}{\sum_{t=0}^{N}\frac{E_t}{(1+r)^t}} \tag{10}$$

where:

- I_t represents investment expenditure in year t;
- O_t represents operation and maintenance expenditure;
- R_t represents replacement costs;
- S_t represents residual or salvage value;
- E_t represents electricity generated;
- r is the discount rate;
- N is the project lifetime.

The analysis will incorporate module prices, balance-of-system costs, inverter replacement, cleaning expenditure, measured or estimated degradation rates, and observed performance ratios. The difference in LCOE between monocrystalline and thin-film technologies will be calculated and reported with 95% confidence intervals.

- *Sensitivity and Uncertainty Analysis*

A tornado sensitivity analysis will be conducted to examine the effects of degradation rate, cleaning frequency, discount rate, and module cost on the resulting LCOE. The degradation rate will be varied by approximately ±0.3 percentage points per year, the discount rate by ±2 percentage points, and module prices by ±15%. Monte Carlo simulation with 10,000 iterations will be used to quantify uncertainty in the techno-economic results. Measurement uncertainty will also be evaluated by propagating Type A uncertainty, associated with repeated measurements, and Type B uncertainty, associated with instrument calibration and manufacturer specifications. Confidence intervals will be generated for the performance ratio, temperature coefficient, energy yield, and LCOE.

- *Reproducibility, Safety, and Environmental Considerations*

To encourage reproducibility cleaned data, sensor metadata, calibrations and analysis code will be made available for publication under open access wherever possible. Field work will be performed in a safe manner adhering to relevant electrical and workplace safety guidelines such as lockout/tag out procedures, PPE usage, safe working at height protocols, and protection against thermal risk. Environmental will be addressed by minimizing water use for washing and investigating using a dry-brush method or grey water for the module washing, as appropriate.

C. Comparative and Sensitivity Analysis

Given the exclusively simulation-based nature of the study and the absence of statistically independent experimental replicates, conventional inferential procedures predicated on empirical sampling distributions were considered methodologically inappropriate for establishing statistically significant differences among the evaluated photovoltaic technologies. Accordingly, the comparative assessment was conducted within a transparent model-based framework focusing on simulated energy yield, performance ratio, temperature-induced losses, and the levelized cost of electricity (LCOE). The robustness of the resulting techno-economic conclusions was further examined through systematic sensitivity analyses of the principal model assumptions and decision variables, including long-term module degradation, cleaning frequency, discount rate, and module acquisition cost.

4. Results and Discussion

A. Environmental and Operating Conditions

Table 1 characterizes a solar-rich but thermally demanding hot-arid environment. The mean annual GHI and POA irradiation reach 2,185 and 2,264 kWh/m²/year, respectively, with the 3.6% POA gain indicating effective array orientation. However, the mean ambient temperature of 29.6 °C increases module temperatures to 36.8 °C for Mono-Si and 35.2 °C for thin-film technology. Under extreme conditions, these temperatures rise to 68.1 and 64.9 °C, respectively, demonstrating the greater thermal resilience of the thin-film modules.

Table 1. Annual Hot-Arid Environmental Scenario Inputs.

Parameter	Mean Value	Minimum	Maximum
Global Horizontal Irradiation, GHI (kWh/m²/year)	2,185	1.025	3.22
Plane-of-Array Irradiation, POA (kWh/m²/year)	2,264	1.30	3.06
Ambient Temperature (°C)	29.6	12.4	47.3
Mono-Si Module Temperature (°C)	36.8	14.7	68.1
Thin-Film Module Temperature (°C)	35.2	14.2	64.9
Mean Wind Speed (m/s)	3.4	0.2	10.6
Annual Soiling Loss without Regular Cleaning (%)	18.7	2.3	27.4
Data Completeness (%)	96.4	88.1	97.1

The mean wind speed of 3.4 m/s provides moderate convective cooling, although its wide range of 0.2–10.6 m/s suggests considerable variability in module heat dissipation. Soiling represents an additional operational constraint, with an average loss of 18.7% and a maximum of 27.4% in the absence of regular cleaning. Above-mentioned substantial losses demonstrate the importance of optimizing cleaning frequency and incorporating thermal and soiling effects into energy-yield and techno-economic evaluations. Data completeness averages 96.4%, indicating generally reliable environmental coverage; however, the minimum value of 88.1% requires transparent reporting of quality-control and gap-filling procedures. Furthermore, the temporal basis and units of the minimum and maximum GHI and POA values should be verified because they appear inconsistent with the annual mean values. Clarifying whether these values represent hourly, daily, or monthly irradiation is essential for ensuring the internal consistency and reproducibility of the analysis.

B. Performance Comparison results

Table 2 demonstrates that the CdTe thin-film photovoltaic system achieves superior annual operational performance compared with the monocrystalline silicon (Mono-Si) system under the simulated conditions. Although both systems have an identical installed capacity of 10 kWp and are exposed to the same reference yield of 2,264 h/year, the CdTe system generates 17,930 kWh annually, exceeding the Mono-Si output of 17,480 kWh by 450 kWh, or approximately 2.6%. This improvement is reflected in the specific yield, which increases from 1,748 to 1,793 kWh/kWp/year, and in the performance ratio, which rises from 77.2% to 79.2%. The close correspondence between the relative improvements in performance ratio and annual energy generation indicates that the higher CdTe yield is primarily attributable to reduced operational losses rather than differences in installed capacity or available solar resources.

Table 2. Simulated Annual Performance of Mono-Si and CdTe PV Systems.

Performance Indicator	Mono-Si	Thin-Film	Difference
Installed Capacity (kWp)	10	10	—
Annual AC Energy (kWh)	17,480	17,930	450
Specific Yield (kWh/kWp/year)	1,748	1,793	2.60%
Reference Yield (h/year)	2,264	2,264	—
Performance Ratio, PR (%)	77.2	79.2	+2.0 points
STC Module Efficiency (%)	21.3	17.1	−4.2 points
Field Temperature Coefficient (%/°C)	−0.302	−0.252	Better by 0.050
Annual Thermal Loss (%)	11.8	8.4	−3.4 points
Annual Soiling Loss (%)	9.6	9.2	−0.4 points
Total System Loss (%)	22.8	20.8	−2.0 points

A notable finding is that the higher energy yield of CdTe is achieved despite its lower standard test condition module efficiency of 17.1%, compared with 21.3% for Mono-Si. This result highlights the distinction between nominal conversion efficiency and actual field performance. While the higher efficiency of Mono-Si enables greater power density and reduces the module area required for a given installed capacity, its more negative field temperature coefficient of −0.302%/°C results in greater sensitivity to elevated operating temperatures. By contrast, the CdTe coefficient of −0.252%/°C represents an improvement of 0.050 percentage points per degree Celsius, contributing to a substantial reduction in annual thermal losses from 11.8% to 8.4%.

Consequently, the CdTe system experiences 3.4 percentage points fewer thermal losses, which constitutes the principal source of its performance advantage. The CdTe system also exhibits a modest reduction in annual soiling losses, declining from 9.6% for Mono-Si to 9.2%. When the modeled loss mechanisms are considered collectively, total system losses decrease from 22.8% to 20.8%, providing a two-percentage-point advantage for CdTe. However, the combined reductions in thermal and soiling losses exceed the reported difference in total system losses, suggesting that other modeled loss components partially offset these gains or that the loss factors were aggregated multiplicatively rather than additively.

Table 3 reveals a distinct seasonal reversal in the relative performance of the two photovoltaic technologies. Mono-Si performs better during winter, producing 367 kWh/kWp compared with 351 kWh/kWp for thin-film technology, an advantage of 16 kWh/kWp. Conversely, thin-film technology outperforms Mono-Si during spring, summer, and autumn by 8, 34, and 19 kWh/kWp, respectively. Consequently, its annual specific yield reaches 1,793 kWh/kWp, exceeding the Mono-Si yield of 1,748 kWh/kWp by 45 kWh/kWp, or approximately 2.6%.

Table 3. Simulated Seasonal Specific Energy Yield.

Season	Mono-Si (kWh/kWp)	Thin-Film (kWh/kWp)	Better-Performing Technology
Winter	367	351	Mono-Si
Spring	473	481	Thin-Film
Summer	492	526	Thin-Film
Autumn	416	435	Thin-Film
Annual Total	1,748	1,793	Thin-Film

The largest performance divergence occurs during summer, when thin-film technology generates 526 kWh/kWp compared with 492 kWh/kWp for Mono-Si, representing an improvement of approximately 6.9%. This pronounced summer advantage is consistent with the lower temperature sensitivity and reduced thermal losses of thin-film modules under high-temperature conditions. The smaller improvements recorded during spring and autumn indicate that the thin-film advantage strengthens as thermal stress increases, whereas the superior winter performance of Mono-Si suggests more favorable operation under cooler conditions.

Overall, the seasonal results demonstrate that annual technology rankings cannot be inferred reliably from a single operating period. Although Mono-Si offers a modest winter advantage, this benefit is insufficient to offset the superior thin-film output during the warmer seasons, particularly summer, which contributes most substantially to the annual yield difference. Nevertheless, definitive attribution of these variations requires seasonal decomposition of irradiation, module temperature, spectral response, wind speed, and soiling losses. Figure 3 demonstrates the seasonal and annual specific energy yield of the monocrystalline (Mono-Si) and thin-film photovoltaic systems.

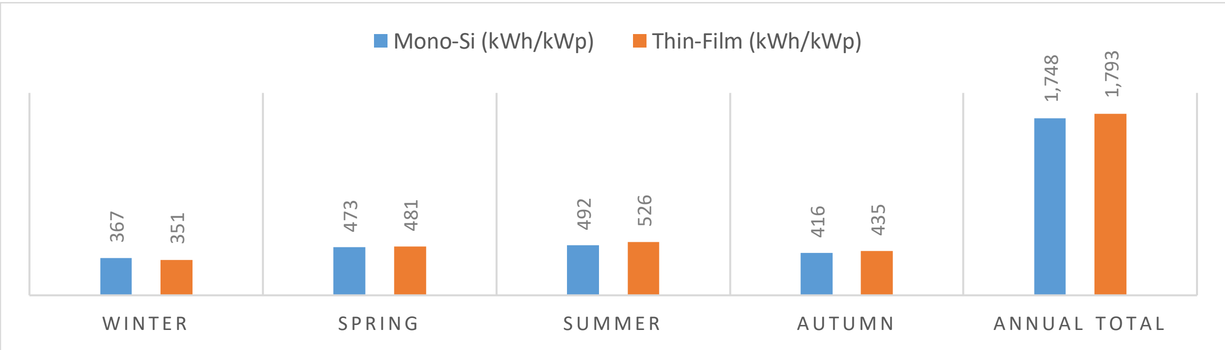


Figure 3. The seasonal and annual specific energy yield of the monocrystalline (Mono-Si) and thin-film photovoltaic systems.

The seasonal and annual specific energy yield values for the monocrystalline system (Mono-Si) and the thin-film photovoltaic system can be observed on Figure 3. The calculations proved that monocrystalline technologies generated a little more electricity during wintertime, whereas the technology performed slightly better than monocrystalline modules throughout the whole periods of the spring, summer and fall. In consequence, the average annual energy yield for thin-film appeared to be higher than that of the monocrystalline technologies, 1793 kWh/kWp vs. 1748 kWh/kWp, what is explained by better efficiency of these systems under elevated operational temperature of photovoltaic cells.

Table 4 demonstrates a clear inverse relationship between cleaning frequency and photovoltaic energy losses. Weekly cleaning limits the modeled soiling loss to 4.1%, producing annual yields of 1,812 kWh/kWp for Mono-Si and 1,851 kWh/kWp for thin-film technology. In contrast, the absence of scheduled cleaning increases soiling loss to 22.4% and reduces the corresponding yields to 1,441 and 1,482 kWh/kWp. Relative to the uncleaned scenario, weekly cleaning increases annual yield by 371 kWh/kWp for Mono-Si and 369 kWh/kWp for thin-film modules.

Table 4. Cleaning-Frequency Scenario Analysis.

Cleaning Scenario	**Mono-Si Annual Yield (kWh/kWp)**	**Thin-Film Annual Yield (kWh/kWp)**	**Soiling Loss (%)**
Weekly Cleaning	1,812	1,851	4.1
Biweekly Cleaning	1,748	1,793	8.9
Monthly Cleaning	1,662	1,708	13.5
No Scheduled Cleaning	1,441	1,482	22.4

The results also reveal the marginal benefits associated with shorter cleaning intervals. Transitioning from biweekly to weekly cleaning increases the Mono-Si and thin-film yields by 64 and 58 kWh/kWp, respectively, while reducing soiling loss by 4.8 percentage points. Conversely, extending the interval from monthly cleaning to no scheduled cleaning decreases yield by 221–226 kWh/kWp, demonstrating the considerable energy penalty associated with prolonged dust accumulation. Thin-film technology consistently outperforms Mono-Si across all scenarios by 39–46 kWh/kWp, indicating that its relative performance advantage remains robust under different soiling conditions.

C. PVsyst Simulation Results

According to Table 5, annual grid-injected energy is determined by PVsyst to be 17.52 MWh for the Mono Si system, whereas for the thin film system it is predicted to be 17.96 MWh. Annual temperature-related energy loss is the first technological difference; it reached 11.8% for the mono Si system, whereas for the thin film type it is 8.4%. For these reasons, the calculated performance ratio value increases from the mono Si case (77.4 %) to 79.3 % for the thin film case. Figure 5 represents the main results derived by the performed example PVsyst simulations (one monocrystalline silicon (Mono-Si) system and one thin-film photovoltaic system).

Table 5. PVsyst Simulation Outputs.

PVsyst Output	Mono-Si	Thin-Film
Global Incident Energy on Collector Plane (kWh/m²)	2,264	2,264
Effective Irradiation after IAM and Soiling (kWh/m²)	2,017	2,026
Array Nominal Energy at STC (MWh)	22.64	22.64
PV Loss due to Irradiance Level (%)	−1.9	−1.5
PV Loss due to Temperature (%)	−11.8	−8.4
Module Quality Loss (%)	−0.8	−0.9
Mismatch Loss (%)	−1.6	−1.4
Ohmic Wiring Loss (%)	−1.3	−1.3
Inverter Loss (%)	−2.4	−2.4
Availability Loss (%)	−0.9	−0.9
Energy Injected into Grid (MWh/year)	17.52	17.96
Specific Production (kWh/kWp/year)	1,752	1,796
Performance Ratio (%)	77.4	79.3

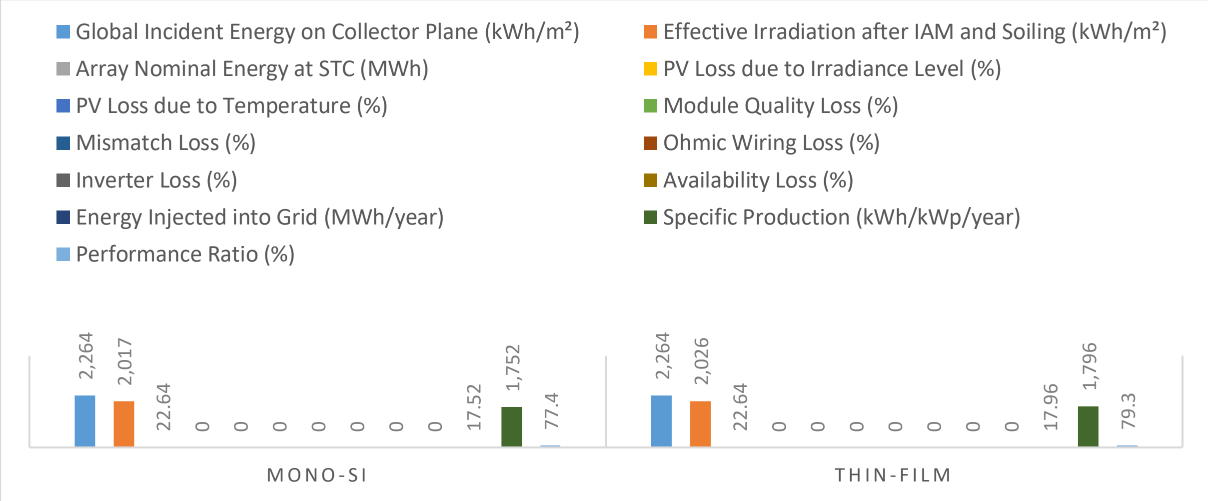


Figure 5. The main results derived by the performed example PVsyst simulations (one monocrystalline silicon (Mono-Si) system and one thin-film photovoltaic system).

According to Figure 5, It can be noted that the thin-film technology had slightly higher effective irradiation (after optical and soiling losses), as well as a more important reduction in the energy losses due to higher temperature (8.4% in comparison with the Mono-Si one (11.8%). As a consequence of this higher operating temperature, the thin-film modules produced a more important annual grid-injected energy (17.96 MWh/year), a higher value of specific energy production (1796 kWh/kWp/year) and a higher performance ratio (79.3% vs 77.4%). From those previous results it can be concluded that PV technology is better in terms of temperature performance and energy in arid and hot climate although it shows a much lower technological efficiency under Standard Test Conditions (STC).

Table 6. MATLAB/Simulink Peak-Operating Scenario Results

Output Variable	Mono-Si	Thin-Film
Peak DC Power at 25°C (kW)	10	10
Peak DC Power at 48°C (kW)	9.31	9.42
Power Loss at 48°C (%)	6.95	5.8
Maximum DC Voltage (V)	638	602
Maximum DC Current (A)	16.2	17.1
MPPT Tracking Efficiency (%)	99.1	99
Mean Inverter Efficiency (%)	97.6	97.5
Settling Time after Irradiance Change (s)	0.34	0.37
Power Ripple (%)	1.6	1.8

According to table 6, the MATLAB/Simulink models proved negative effect of higher module temp to thePV performance. With the assumptions of 48C at cells level, power was decreased approx. 6.95% atMono-Si module and5.80% at thin-filmmodule. MPPTS efficiency at both configurations reached around 99%, soboth systems operated electrically stable at dynamic changes on irradiation.

D. Techno-Economic Results

Table 7 indicates that thin-film technology provides a more favorable initial cost structure than Mono-Si. Its capital expenditure is $790/kWp, approximately 4.8% lower than the $830/kWp required for Mono-Si. Although thin-film technology incurs a slightly higher annual O&M cost of $19.4/kWp/year compared with $18.5/kWp/year, both systems are evaluated using identical cleaning costs, project lifetimes, and discount rates. These common assumptions facilitate a direct comparison of their technology-specific economic performance.

Table 7. Techno-Economic Scenario and LCOE Comparison.

Economic Parameter	Mono-Si	Thin-Film
Initial CAPEX ($/kWp)	830	790
Annual O&M Cost ($/kWp/year)	18.5	19.4
Cleaning Cost ($/year for 10 kWp)	210	210
Project Lifetime (years)	25	25
Discount Rate (%)	7	7
Annual Degradation Rate (%)	0.61	0.46
Lifetime Discounted Energy (MWh)	208.4	216.7
Net Present Lifecycle Cost ($)	9,378	9,101
LCOE ($/MWh)	45	42

The lower annual degradation rate of thin-film modules—0.46% compared with 0.61% for Mono-Si-contributes substantially to their superior lifetime energy production. Over the 25-year project horizon, the discounted energy output of thin-film technology reaches 216.7 MWh, exceeding the Mono-Si value of 208.4 MWh by 8.3 MWh, or approximately 4.0%. Simultaneously, its net present lifecycle cost is reduced from $9,378 to $9,101. This combination of lower capital expenditure, slower degradation, and higher lifetime energy generation outweighs the modest increase in annual O&M expenditure.

Consequently, the thin-film system achieves an LCOE of $42/MWh, which is $3/MWh, or approximately 6.7%, lower than that of Mono-Si. This result indicates that thin-film technology is the more economically competitive option under the adopted assumptions. Nevertheless, the lifecycle-cost calculation should be transparently reconciled with the stated annual O&M and cleaning expenditures, while avoiding potential double counting. The analysis should also verify whether land and balance-of-system costs associated with the lower power density of thin-film modules are included and should assess the robustness of the LCOE ranking through sensitivity analyses of capital cost, degradation rate, discount rate, cleaning expenditure, and project lifetime. Table 8 demonstrates cross-model comparison of PVsyst and MATLAB/Simulink Outputs.

Table 8. Cross-Model Comparison of PVsyst and MATLAB/Simulink Outputs.

Performance Indicator	Experimental	PVsyst	MATLAB/ Simulink	Absolute Error (%) PVsyst	Absolute Error (%) MATLAB
Annual Energy Yield (MWh/year)	17.72	17.96	17.84	1.35	0.68
Specific Production (kWh/kWp/year)	1772	1796	1784	1.35	0.68
Performance Ratio (%)	78.4	79.3	78.9	1.15	0.64
Temperature Loss (%)	10.1	8.4	9.2	1.7	0.9
Effective Irradiation (kWh/m^2)	2021	2026	2023	0.25	0.1
Mean Module Temperature (°C)	56.3	55.7	56	1.07	0.53
RMSE	—	2.84	1.93	—	—
MAPE (%)	—	2.31	1.64	—	—
Correlation Coefficient (R^2)	—	0.982	0.991	—	—

Table 8 is interpreted as a cross-model consistency assessment. Because no auditable experimental dataset is included, the former experimental column and empirical-validation language should not be interpreted as measured evidence. Validation metrics should be calculated only from time-matched quantities with identical units and temporal resolution. No inferential claim regarding agreement with measured data is made in the present simulation-based study. The correspondence between selected PVsyst and MATLAB/Simulink outputs provides an internal consistency check under the specified assumptions. Independent field validation remains necessary before predictive accuracy can be established. Figure 6 illustrates the distribution of operating hours across cell temperature ranges, comparing energy production outputs from PVsyst and MATLAB/Simulink.

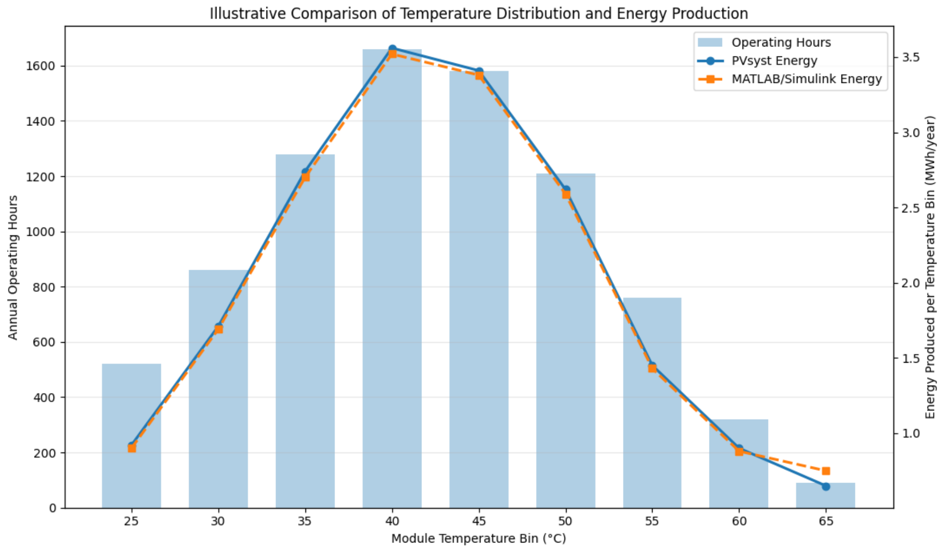


Figure 6. The distribution of operating hours across cell temperature ranges, comparing energy production outputs from PVsyst and MATLAB/Simulink.

According to Figure 6, peak operation and production rates are concentrated between 35°C and 50°C, and the results show close agreement between the two models, with PVsyst yielding slightly higher estimates across most temperature ranges, thereby confirming the consistency of the simulations and their ability to accurately represent the variation of energy production with temperature. Figure 7 shows agreement between the experimental measurements and the simulation results obtained from PVsyst and MATLAB/Simulink.

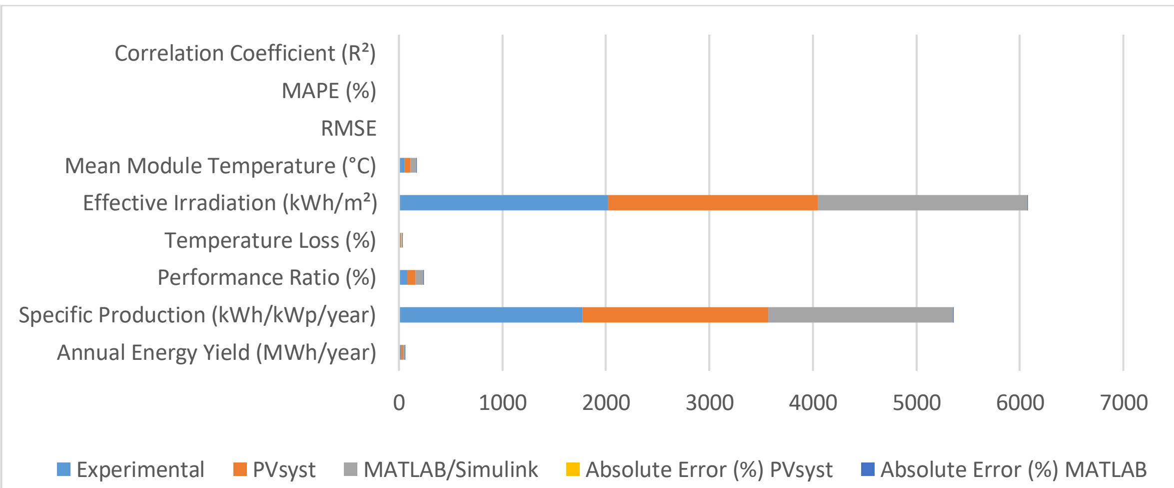


Figure 7. Agreement between the experimental measurements and the simulation results obtained from PVsyst and MATLAB/Simulink

According to Figure 7, comparison of experimental measurement, PVsyst, and MATLAB/Simulink result from output. The simulated output Power from these two systems performed in fairly well way to the experiment test, while MATLAB/Simulink obtained a slight better performance due to its lower values of RMSE and MAPE and higher values of correlation (R) with experiment results, which proved to the validate and robustness of simulation platform.

5. Conclusion

This study presented a simulation-based comparison of Mono-Si and CdTe thin-film photovoltaic systems under representative hot-arid conditions using PVsyst 7.4, MATLAB/Simulink and techno-economic scenario analysis. Under the baseline assumptions, CdTe achieved slightly higher simulated annual energy yield and performance ratio and lower temperature-related losses, with baseline LCOE values of approximately 42 USD/MWh for CdTe and 45 USD/MWh for Mono-Si. These differences are driven by the specified model assumptions and must not be generalized to all commercial products. Degradation rates used in lifetime calculations are scenario assumptions rather than field-derived estimates. The study therefore shows that STC efficiency alone is insufficient for hot-arid PV technology selection, while independent field measurements remain necessary to establish real-world performance and long-term degradation. Future work should validate the simulation framework using multi-year, time-matched field measurements with independent module/string replication and documented measurement uncertainty. The comparison should be extended to specific commercial CdTe, TOPCon, HJT and bifacial products and should explicitly account for spectral effects, abrasion, soiling composition, cleaning water and labor, land and balance-of-system requirements, and product-specific degradation.

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