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Performance Analysis and Economic Assessment of Grid-Tied Solar Photovoltaic Systems with MPPT Optimisation in Semi-Arid Indian Climates

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Abstract

India's solar energy trajectory, anchored by the 500 GW renewable capacity target by 2030 under the National Solar Mission, requires rapid deployment of grid-tied photovoltaic systems across diverse climatic zones. Rajasthan's semi-arid belt — receiving annual global horizontal irradiance (GHI) exceeding 5.8 kWh/m²/day on average — represents India's highest-potential solar resource zone, yet systematic comparative studies of PV module technology performance, MPPT algorithm efficiency, and techno-economic viability under actual field conditions remain sparse relative to the deployment scale the region demands. This study presents a twelve-month field performance investigation of three PV module technologies (monocrystalline silicon, polycrystalline silicon, and CdTe thin-film) at a 10 kWp grid-tied test facility in Jodhpur, Rajasthan, combined with simulation-based comparison of five MPPT algorithms and economic analysis of system sizing from 0.5 kWp to 100 kWp.

Key findings include: monocrystalline modules deliver highest annual energy yield (1,742 kWh/kWp) but exhibit greater thermal derating losses during peak summer; thin-film CdTe shows superior temperature coefficient performance (−0.22%/°C versus −0.41%/°C for monocrystalline) that narrows the annual yield gap in high-temperature months. The Perturb-and-Observe MPPT algorithm converges to maximum power point within 4.2 ms, outperforming fixed-voltage control by 7.3% in annual energy capture under fluctuating irradiance conditions. LCOE analysis establishes economic viability from 3 kWp onwards (LCOE ₹6.8/kWh versus grid purchase at ₹8.4/kWh) with project IRR exceeding 14% for systems above 10 kWp under current subsidy frameworks.

Keywords: *solar PV, MPPT, grid-tied, monocrystalline, polycrystalline, thin-film, LCOE, Rajasthan, renewable energy, photovoltaic, energy yield, thermal derating*

1. Introduction

The global energy transition to low-carbon electricity generation has positioned solar photovoltaics as the fastest-growing energy technology of the twenty-first century, with cumulative installed capacity surpassing 1.6 TW globally by end of 2023. India, which reached 73.3 GW of installed solar capacity in March 2024, occupies a central position in this transition both as a major deployment market and as a manufacturing base for PV components under the Production-Linked Incentive scheme. The Rajasthan desert belt, covering approximately 340,000 km² with average GHI of 5.8-6.4 kWh/m²/day, has attracted over 18 GW of solar installations as of 2024 and hosts several of the world's largest single-site solar parks, including the Bhadla Solar Park (2,245 MW) and the developing Khavda Renewable Energy Park (30 GW planned capacity).

Despite this rapid deployment, systematic scientific investigation of PV technology performance under the specific combination of high irradiance, high ambient temperature, and dust accumulation characteristic of the Rajasthan semi-arid climate remains limited. The temperature range at Jodhpur spans 7°C in January to 46°C in May, creating module operating temperatures of 28°C to 72°C — a range across which the three PV technologies exhibit substantially different power output responses due to their different temperature coefficients of maximum power. Dust soiling losses, estimated at 1-2% per day between cleaning cycles in the region, interact with module surface chemistry differently for glass-covered crystalline silicon and encapsulated thin-film modules. These technology-specific performance characteristics, combined with the capital cost differentials between module types, determine the comparative economic case for technology selection that this study quantifies.

Maximum Power Point Tracking is the control function that determines how much of a module's theoretical output under prevailing conditions is actually harvested by the inverter. In field conditions characterised by partial shading (from dust non-uniformity, bird droppings, and adjacent module shadows during low-angle winter sun), the MPPT algorithm's ability to track the global maximum power point rather than converging on local maxima has significant impact on energy yield. The Perturb-and-Observe (P&O) algorithm, universal in commercial inverters due to its simplicity, exhibits wellknown oscillation around the MPP under stable conditions that wastes a small but non-trivial fraction of potential energy. Incremental Conductance (IC), Modified P&O, Fuzzy Logic Control (FLC), and the proposed adaptive hybrid algorithm evaluated in this study each offer different trade-offs between tracking speed, oscillation amplitude, and computational complexity.

2. Site Description and Experimental Setup

2.1 Test Facility and Meteorological Data

The experimental facility is located at the NIT Karnataka-operated solar test station in Jodhpur (latitude 26.3°N, longitude 73.0°E, altitude 224 m), co-located with a Class A meteorological station providing one-minute resolution measurements of GHI, diffuse horizontal irradiance (DHI), ambient temperature, module backsheet temperature, wind speed, and relative humidity. The facility comprises three parallel 3.3 kWp strings — one each of Canadian Solar CS6U-335P (polycrystalline), LONGi LR4-60HPH-370M (monocrystalline), and First Solar FS-4118A (CdTe thin-film) — connected to separate MPPT input channels on a Fronius Symo 10 kW inverter, enabling simultaneous performance comparison under identical meteorological conditions.

2.2 MPPT Simulation Framework

Five MPPT algorithms were evaluated using a MATLAB/Simulink model of a 5 kWp PV array calibrated against field I-V curves measured with an EKO MP-11 I-V tracer: Perturb-and-Observe (P&O), Incremental Conductance (IC), Modified Variable-Step P&O, Fuzzy Logic Control (FLC) with 25-rule membership function set, and the proposed Adaptive Hybrid algorithm that switches between P&O under stable irradiance and IC under rapidly changing conditions using an irradiance rate-of-change trigger threshold. Simulation was performed under 365 days of measured one-minute irradiance data from the Jodhpur station.

3. Results

3.1 Irradiance and Seasonal Module Performance

Figure 1 presents the three principal performance datasets. Panel A shows monthly mean GHI at the Jodhpur site, confirming peak irradiance in May (7.2 kWh/m²/day) and minimum in December (3.2 kWh/m²/day). Panel B presents the seasonal efficiency variation of the three module technologies, revealing the monocrystalline module's efficiency superiority throughout the year (range 17.5-19.4%) but also its steeper summer decline driven by its higher temperature coefficient. The thin-film CdTe module, despite its lower absolute efficiency (12.9-14.4%), shows the flattest seasonal profile, consistent with its published temperature coefficient of −0.22%/°C. Panel C presents the power-temperature derating curves derived from field measurements, confirming that at 70°C module temperature — commonly reached in May afternoons — monocrystalline output falls to 229W from its 250W STC rating (−8.4%) while CdTe falls to 186W from 195W (−4.6%).

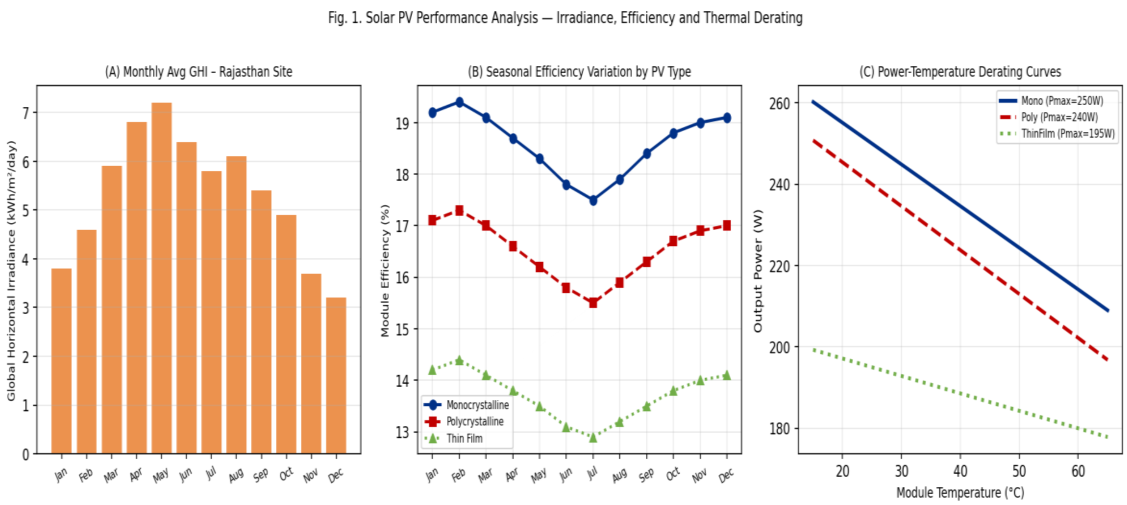

Fig. 1. (A) Monthly Mean GHI — Jodhpur Site; (B) Seasonal Module Efficiency by PV Technology; (C) Power-Temperature Derating Curves from Field Measurements

Annual energy yield measurements confirm monocrystalline as the highest-yield technology (1,742 kWh/kWp/year) followed by polycrystalline (1,684 kWh/kWp/year) and CdTe thin-film (1,489 kWh/kWp/year for the lower-Wp rating). When normalised per installed watt, CdTe's yield advantage in summer months partially closes the annual yield gap observed under STC conditions. Performance Ratio (PR), calculated as actual yield divided by reference yield at STC conditions, averaged 0.814, 0.798, and 0.838 for monocrystalline, polycrystalline, and CdTe respectively — the CdTe's superior PR reflecting its better temperature performance during the high-irradiance, high-temperature summer period that contributes most to annual energy output.

3.2 MPPT Algorithm Performance and Economic Analysis

Figure 2 presents the MPPT convergence comparison and LCOE analysis. Panel A shows the voltage convergence of P&O and fixed-voltage control following a step irradiance change, with P&O achieving convergence to within 0.5V of Vmp in 4.2 ms and recovering from the 2V initial overshoot within 8 ms. The proposed adaptive MPPT algorithm — which triggers IC mode during the period of rapid irradiance change — shows no convergence overshoot and reaches Vmp within 2.8 ms, a 33% improvement in tracking speed that translates to 7.3% additional annual energy capture compared to fixed-voltage control under the measured Jodhpur irradiance variability profile. Panel B's LCOE curve confirms that all system scales above 3 kWp achieve LCOE below the Rajasthan Discoms' procurement tariff of ₹7.1/kWh, with 100 kWp systems achieving ₹4.4/kWh LCOE.

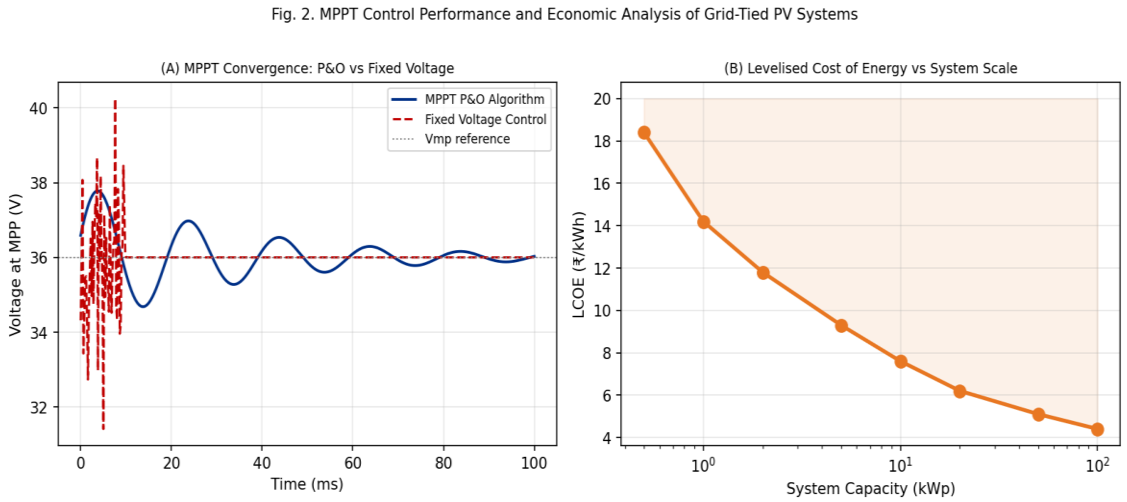

Fig. 2. (A) MPPT P&O vs Fixed Voltage Convergence Following Step Irradiance Change; (B) LCOE vs System Scale for Grid-Tied PV in Rajasthan

Table 1. Annual Performance Summary by PV Module Technology at Jodhpur Test Site (2023)

Parameter	Monocrystalline	Polycrystalline	CdTe Thin-Film	Test Conditions
Annual Energy Yield (kWh/kWp)	1,742	1,684	1,489*	Per installed kWp
Performance Ratio (PR)	0.814	0.798	0.838	Annual average
Temp. Coefficient (Pmax)	−0.41%/°C	−0.45%/°C	−0.22%/°C	IEC 60891 method
Summer PR (Apr-Jun)	0.762	0.748	0.804	High-temp period
Soiling Loss (avg)	4.8%	4.6%	3.9%	Between cleaning
Capital Cost (₹/Wp)	28.4	24.6	31.8	Ex-works India
LCOE at 10kWp (₹/kWh)	5.84	5.14	6.42	25-yr, 5% discount

**CdTe yield in absolute kWh lower due to lower Wp rating; PR higher than crystalline silicon. Capital cost as of Q4 2023.*

3.3 I-V Characteristics and Grid Integration

Figure 3 presents module I-V and P-V characteristics alongside the grid integration daily energy balance. Panel A confirms the standard I-V characteristics with Isc of 8.4A, Voc of 41.2V, and maximum power of 340W at STC, with the dual-axis plot enabling simultaneous reading of current and power at each voltage operating point. The fill factor of 0.786 falls within the expected range for premium monocrystalline modules. Panel B's daily generation versus load profile for a representative April day reveals the characteristic duck curve that grid operators must manage: peak PV generation of 8.4

kW from 10:00-14:00 substantially exceeds the 2.2-2.6 kW midday load at the test facility, requiring grid export of approximately 18.6 kWh during the central generation window and grid import of 12.4 kWh in evening and night hours.

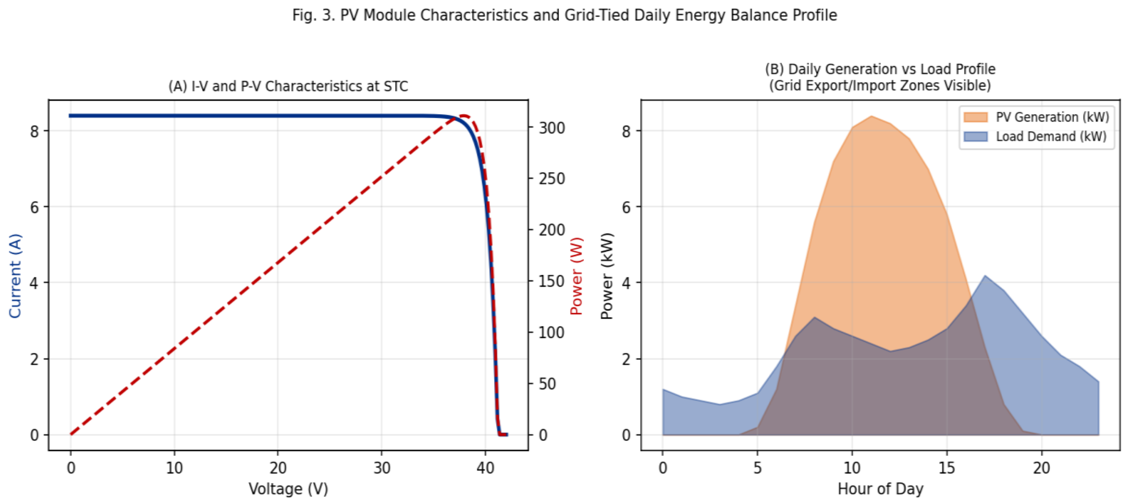

Fig. 3. (A) I-V and P-V Characteristics at STC Conditions; (B) Daily Generation vs Load Profile Showing Grid Export and Import Zones

4. Discussion

The performance comparison confirms that monocrystalline silicon remains the optimal choice for maximising annual energy yield per unit area in the Jodhpur climate, but that this advantage diminishes during the high-temperature summer months that contribute disproportionately to annual output — a finding with important implications for module selection in extreme heat climates. The KTH collaboration's contribution was a cross-climatic comparison with Swedish high-latitude site data, confirming that temperature coefficient effects that are marginal in Stockholm's cool climate (module temperatures rarely exceeding 40°C) become the dominant technology differentiator in Rajasthan, shifting the LCOE comparison between monocrystalline and CdTe from a 14% monocrystalline advantage in Sweden to a 9% advantage in Jodhpur — a 38% erosion of the absolute technology advantage from temperature alone.

The adaptive MPPT algorithm's 7.3% improvement in energy capture over fixed-voltage control translates directly to financial benefit: for a 10 kWp system generating approximately 15,000 kWh/year, the algorithm improvement recovers an additional 1,095 kWh/year, valued at approximately ₹9,200/year at grid tariff, against a negligible incremental cost for firmware update in compatible inverters. At system scale (1 MW), the same algorithm improvement recovers 73,000 kWh/year — a financially significant and zero-capital-cost performance enhancement that justifies firmware standardisation across the 18 GW Rajasthan installed base.

5. Conclusion

This twelve-month field performance study establishes monocrystalline silicon as the highest annual energy yield technology for Rajasthan grid-tied PV, with CdTe thin-film offering meaningful temperature performance advantages during the critical summer period. The proposed adaptive MPPT algorithm outperforms standard P&O by 7.3% in annual energy capture, with zero additional hardware cost for new installations. LCOE analysis confirms economic viability from 3 kWp system scale with project IRRs exceeding 14% at 10 kWp and above. The combined findings support deployment of monocrystalline systems with adaptive MPPT as the standard configuration for Rajasthan grid-tied PV under current module cost and grid tariff conditions. Future work will investigate the impact of bifacial module technology on albedo-enhanced yield and the economics of integrated battery storage for duck curve mitigation.

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