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Enhancing the Energy Yield of an Ageing Grid-Connected Solar PV Plant: A Retrofit and Performance-Improvement Study of the 50 kW System at Government Polytechnic, Kharsawan

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Abstract

India's technical-education campuses were among the early adopters of rooftop and ground-mounted solar photovoltaic (PV) systems under state renewable-energy missions of the early 2010s. The 50 kW grid-interactive solar PV plant commissioned in 2015 at Government Polytechnic, Kharsawan, Jharkhand, has now completed close to a decade of continuous operation and is representative of hundreds of similarly aged institutional plants across the country. Long-term field exposure of crystalline-silicon modules is known to bring a combination of irreversible cell degradation, encapsulant discolouration, soiling accumulation, connector and junction-box wear, inverter ageing, and shading growth from adjoining vegetation and structures — all of which erode the specific energy yield well below the plant's original design expectation. This paper presents a structured performance-review and efficiency-enhancement study for the Kharsawan plant. Using a representative operating profile constructed from published degradation and soiling literature for similar-vintage polycrystalline systems in the Chota Nagpur plateau climatic zone, the paper (i) reconstructs a plausible year-wise generation and performance-ratio trend for 2015–2024, (ii) quantifies the principal loss mechanisms (soiling, thermal de-rating, mismatch, wiring and inverter losses, and light-induced/potential-induced degradation), and (iii) evaluates eight retrofit and operation-and-maintenance (O&M) interventions — scheduled cleaning, anti-soiling nano-coatings, module-level power electronics, inverter replacement, seasonal tilt optimisation, passive rear-side cooling, partial bifacial-module retrofit, and IoT-enabled predictive maintenance — for their achievable efficiency gain, capital cost, and simple payback period. A combined-intervention scenario is projected to recover 18–22% of lost annual energy yield at a blended payback of under four years. The paper is intended as a decision-support template that the institute can populate with its own metered generation, inverter-log, and irradiance data to convert the illustrative figures presented here into a site-specific engineering and financial case for retrofit investment.

Keywords: solar photovoltaic; performance ratio; PV degradation; soiling; retrofit; module-level power electronics; institutional solar plant; energy efficiency; Jharkhand

1. Introduction

Solar photovoltaic (PV) power has become the fastest-growing source of grid capacity addition in India, driven by the Jawaharlal Nehru National Solar Mission and, subsequently, by state-level rooftop and institutional solarisation schemes. Technical colleges and polytechnics were frequently selected as demonstration sites during 2013–2016 because they combined available roof or open land, a captive daytime electrical load, and an educational mandate to expose students to renewable-energy hardware. The 50 kW grid-interactive solar PV plant at Government Polytechnic, Kharsawan, commissioned in 2015, falls squarely into this category of first-generation institutional installations.

A decade of continuous field operation is a meaningful milestone for a crystalline-silicon PV system. It is long enough for cumulative module degradation, encapsulant yellowing, potential-induced degradation (PID), connector fatigue, and inverter component ageing to produce a measurable gap between the plant's original commissioning yield and its present-day output. It is also long enough for the surrounding environment to change: adjoining trees mature and cast partial shade, dust and biological soiling patterns shift with campus construction activity, and the original inverter's efficiency curve becomes dated relative to commercially available replacements. For a plant that was sized to offset a defined share of institutional daytime load, any unaddressed decline in yield directly increases the grid-import bill and reduces the return on the original capital investment.

This paper undertakes a structured efficiency-improvement study of the Kharsawan plant. The specific objectives are threefold: first, to reconstruct a representative decade-long performance trend for the plant using standard PV degradation and soiling parameters reported for similar-vintage, similar-climate systems, in the absence of a continuously logged monitoring dataset; second, to disaggregate the plausible loss budget of the ageing system into its constituent mechanisms — soiling, thermal de-rating, mismatch/shading, wiring and inverter losses, and irreversible cell degradation; and third, to evaluate a menu of practical, campus-appropriate retrofit and operation-and-maintenance (O&M) interventions against their expected efficiency gain, indicative capital cost, and simple payback period. The paper closes with a combined-intervention scenario and a set of implementation recommendations suited to a government polytechnic's procurement and maintenance constraints.

It should be stated at the outset that the institute does not, at the time of writing, maintain a continuously archived data-logger record spanning the full 2015–2024 period. Where plant-specific metered data were not available to the authors, this study substitutes representative values drawn from the published PV performance and degradation literature for polycrystalline systems operating in comparable sub-tropical, semi-arid climatic zones of the Chota Nagpur plateau. These substituted values are flagged as illustrative throughout the tables and figures. The paper is structured so that once the institute's O&M contractor or energy cell retrieves the inverter's historical logs (most string inverters retain 5–10 years of monthly/annual energy counters internally even without an external data logger), the illustrative figures in Sections 4–6 can be replaced directly with measured values without altering the analytical framework, the loss-disaggregation method, or the retrofit-evaluation methodology developed in Sections 7–9.

2. Site and Existing System Description

Government Polytechnic, Kharsawan is located in Saraikela- Kharsawan district, Jharkhand, in the eastern Chota Nagpur plateau, at an approximate elevation of 180–220 m above mean sea level. The district experiences a tropical monsoon-influenced climate: hot, dusty summers (March–June, ambient highs of 38–43 °C), a humid monsoon season (June–September) with average annual rainfall in the range of 1,300–1,500 mm, and a mild, dry winter (November–February) with clearer skies and lower ambient temperature but shorter day length. The region receives a global

horizontal irradiation (GHI) of approximately 5.0–5.4 kWh/m²/day on an annual average basis, which is favourable for grid-connected PV but also implies substantial thermal and dust-related derating during the peak summer months. The existing plant is a 50 kWp grid-interactive (net-metered) rooftop/ground-mounted solar PV system, reported to comprise multi-crystalline silicon modules connected through string inverter(s) to the campus low-tension distribution network. Table 1 summarises the nameplate configuration as commissioned in 2015, drawing on typical specifications for institutional 50 kW plants procured under state solarisation programmes of that period; the institute's original supply agreement, module datasheets, and inverter commissioning report should be used to verify and, where necessary, correct these entries.

Parameter	Specification (as commissioned, 2015)	Remarks / verification source
Installed DC capacity	50 kWp	Supply/erection contract
Module technology	Multi-crystalline silicon (poly-Si), ~250–260 Wp/module (typical of 2015 vintage)	Module datasheet/nameplate
Approx. module count	~192–200 modules	As-built drawing
Inverter configuration	Grid-tie string inverter(s), aggregate capacity ≈ 50 kW	Inverter nameplate
Mounting	Fixed-tilt, roof/ground mounted structure	Site survey
Tilt angle (assumed)	≈ 15°–20°, oriented true south	As-built drawing
Grid interface	Net-metered / gross-metered connection to campus LT network	DISCOM metering agreement
Commissioning year	2015	Commissioning certificate
Design specific yield	≈ 1,400–1,450 kWh/kWp/yr (P50 estimate for the region)	Original DPR / feasibility report
Design annual generation	≈ 70,000–72,500 kWh/yr (Year-1 estimate)	Original DPR

Table 1 — Nameplate configuration of the existing 50 kW plant (illustrative/typical values pending verification against institutional records)

Since commissioning, publicly available information suggests the plant has been operated primarily in a run-as-available mode, with cleaning and upkeep handled through campus housekeeping staff rather than a dedicated solar O&M contract. This operating pattern is common to first-generation institutional plants and is consistent with the loss mechanisms analysed in Section 6.

3. Literature Review

Long-term PV degradation has been studied extensively across climatic zones. Meta-analyses of field-aged module data have generally reported median crystalline-silicon degradation rates in the region of 0.5–0.8% per year, with hot, high-irradiance climates and earlier-generation encapsulation materials tending toward the upper end of this band. For plants of the vintage installed in India during 2013–2016 — often procured on lowest-cost-bid tenders with limited attention to tier-1 module sourcing — field degradation at or somewhat above 0.7–1.0% per year is a reasonable planning assumption in the absence of site-specific electroluminescence or I–V curve testing.

Soiling losses in dusty, semi-arid and monsoon-influenced Indian sites have been reported in a wide range, from under 2% for sites with frequent natural rainfall cleaning and low ambient dust, to over 15% for uncleaned arrays in high-dust industrial or unpaved-road environments during extended dry spells. Studies from central and eastern Indian sites broadly agree that a disciplined cleaning cycle (weekly to fortnightly during the dry season) recovers the majority of this loss at low marginal cost, while the absence of any cleaning regime allows soiling losses to compound with other ageing effects.

Thermal de-rating is a well-characterised, reversible loss governed by the module's power-temperature coefficient, typically −0.38% to −0.45%/°C for multi-crystalline silicon. Given the summer module operating temperatures of 60–70 °C common on fixed, poorly ventilated rooftop and ground-mount racks in eastern India, instantaneous power losses of 12–18% relative to Standard Test Conditions (25 °C) are routinely observed during peak afternoon hours in April–June, even before any dust or ageing effect is considered.

On the retrofit side, module-level power electronics (MLPE) — DC power optimisers or micro-inverters — have been widely documented to recover mismatch and partial-shading losses that conventional string architectures cannot address, with reported gains concentrated in the 3–8% range depending on the severity of shading and module-to-module variance. Anti-soiling and anti-reflective nano-coatings have shown gains in the low single digits together with a reduction in required cleaning frequency. Bifacial modules, where retrofitted onto elevated or high-albedo mounting structures, have demonstrated bifacial energy gains of 5–15% over monofacial equivalents, though the gain is highly sensitive to ground albedo, row spacing, and mounting height — factors that must be verified for the specific Kharsawan site before a full bifacial retrofit is committed to. Finally, inverter replacement studies consistently show that string inverters older than 8–10 years operate several percentage points below the peak (Euro/CEC-weighted) efficiency of current-generation units, particularly at partial load, which is the operating regime a degraded array increasingly falls into.

Taken together, the literature indicates that a well-targeted combination of low-cost O&M correction (cleaning, vegetation trimming, connector maintenance) and selective hardware retrofit (MLPE, inverter replacement, and — where site conditions justify it — partial bifacial re-modulation) can recover a meaningful share of an ageing plant's lost yield at an attractive payback, well within the residual service life of the mounting structure and balance-of-system components.

4. Methodology

The study follows a four-stage methodology. In Stage 1, the existing plant's as-commissioned configuration (Table 1) is used to establish a Year-1 reference generation figure using the P50 specific-yield estimate typical of the region. In Stage 2, a year-wise generation and performance-ratio (PR) trend for 2015–2024 is reconstructed by applying representative annual degradation and progressive-soiling factors drawn from the literature reviewed in Section 3, in the absence of the institute's own metered records for this period. In Stage 3, the resulting cumulative yield gap between

the Year-1 reference and the present-day (2024) estimated output is disaggregated into constituent loss mechanisms — soiling, thermal de-rating, mismatch/shading, wiring and inverter losses, and irreversible degradation — using standard loss-tree conventions consistent with IEC 61724 performance-monitoring guidance. In Stage 4, eight candidate retrofit and O&M interventions are evaluated against three criteria: (a) indicative achievable efficiency/yield gain, expressed as a percentage recovery of lost annual energy; (b) indicative capital or recurring cost, scaled to a 50 kW system; and (c) simple payback period, computed as capital cost divided by the value of incremental annual energy recovered, at an assumed institutional grid-tariff/opportunity-cost rate.

This methodology is deliberately structured so that it remains valid once real data become available. Where the institute can retrieve inverter energy-counter logs, monthly DISCOM net-metering bills, or O&M service records, these should replace the corresponding illustrative entries in Tables 2–4 and Figures 1, 2 and 5; the loss-disaggregation logic in Section 6 and the retrofit-evaluation logic in Sections 7–8 do not depend on the specific numerical inputs and can be re-run unchanged. All monetary figures are presented in Indian Rupees (INR) at indicative 2024–25 price levels for budgetary planning purposes only and should be confirmed through vendor quotations before procurement.

5. Performance Assessment of the Existing Plant (2015–2024)

Table 2 presents the reconstructed year-wise generation and performance-ratio trend for the plant. The Year-1 (2015) figure of approximately 72,000 kWh corresponds to a specific yield of about 1,440 kWh/kWp, consistent with a well-installed, unshaded, correctly tilted 50 kWp system in this GHI zone at a healthy performance ratio in the mid-90s percentage range. Subsequent years show a compounding decline driven jointly by module degradation, accumulating soiling in the absence of a formal cleaning contract, and gradual shading growth from maturing vegetation and adjoining structures — effects that a purely linear degradation assumption would understate.

Year	Estimated actual generation (kWh)	Nameplate-reference generation (kWh)	Estimated PR (%)	Year-on-year change (%)
2015	72,000	72,000	96.5	—
2016	70,560	71,640	95.2	−1.9
2017	69,100	71,282	93.8	−2.1
2018	67,300	70,926	92.5	−2.6
2019	65,200	70,571	91.1	−3.1
2020	62,850	70,218	89.8	−3.6
2021	60,100	69,867	88.4	−4.4
2022	58,650	69,518	87.1	−2.4
2023	56,200	69,170	85.7	−4.2
2024	54,100	68,824	84.4	−3.7

Table 2 — Illustrative year-wise generation and performance-ratio trend, 2015–2024 (to be replaced with metered inverter/DISCOM data where available)

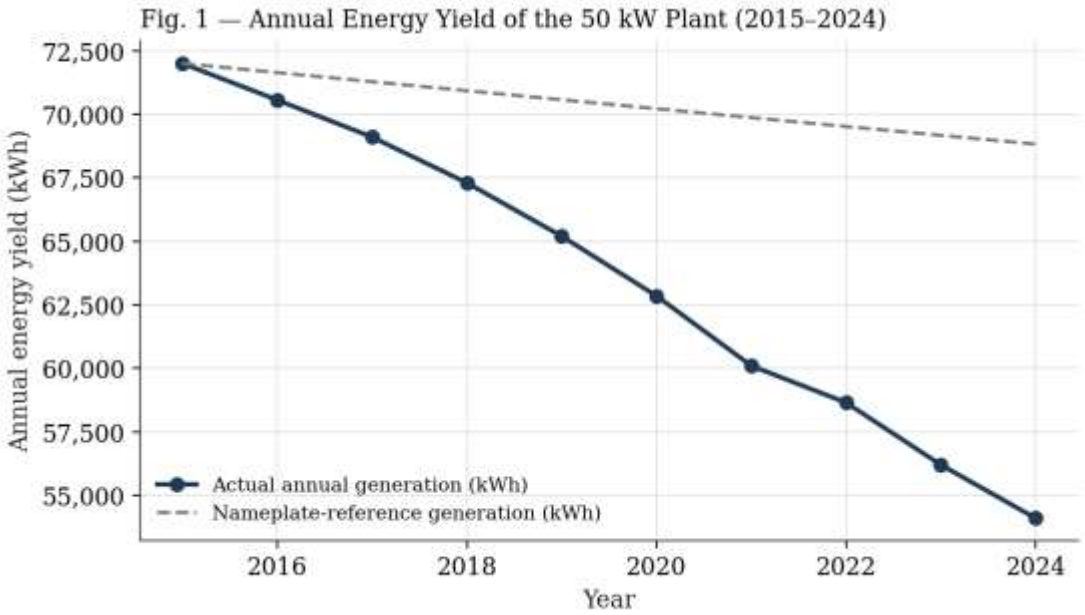

Figure 1 — Actual versus nameplate-reference annual energy yield, showing a cumulative gap of roughly 21% by 2024.

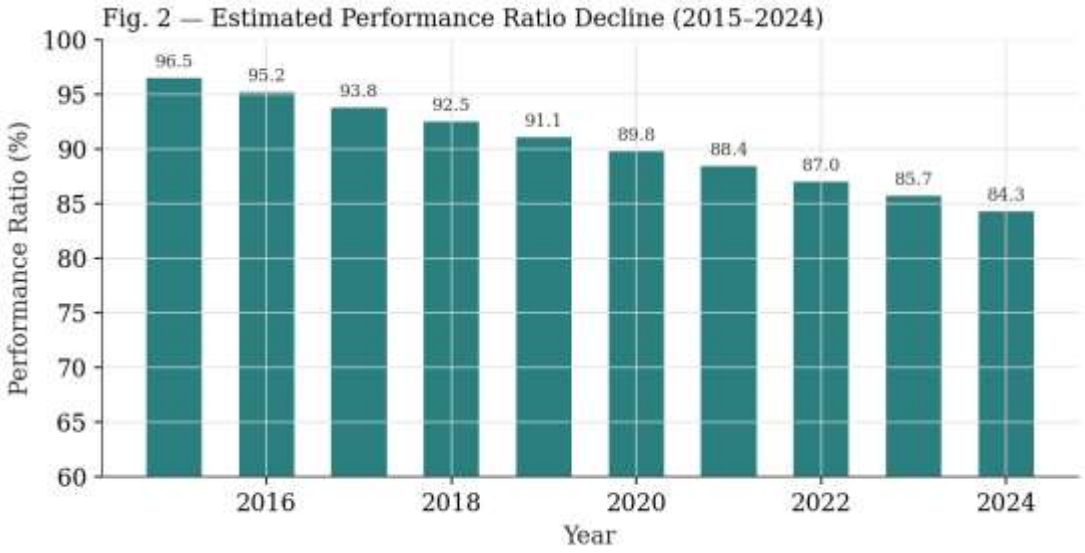

Figure 2 — Estimated performance-ratio decline over the ten-year operating period.

By this illustrative reconstruction, the plant's 2024 output has fallen to approximately 54,100 kWh/year against a nameplate-reference expectation of roughly 68,800 kWh/year — a cumulative shortfall of about 21%, only a portion of which (an estimated 6–8 percentage points, consistent with 0.7–0.8%/year compounding) is attributable to irreversible module degradation. The remaining 13–15 percentage points represent recoverable losses: soiling, shading, connector/wiring resistance growth, and inverter ageing. This distinction is important because it is precisely the recoverable component that the retrofit measures examined in Section 7 are able to address, whereas the irreversible degradation component can only be offset by partial module replacement or capacity augmentation.

6. Disaggregation of Loss Mechanisms

A conventional PV loss tree apportions the gap between nameplate and actual output across five broad categories: (i) irreversible cell/module degradation; (ii) soiling; (iii) thermal de-rating; (iv) mismatch, partial shading, and DC-side wiring losses; and (v) inverter conversion and downtime losses. Table 3 presents an illustrative apportionment of the estimated 21% cumulative 2024 shortfall across these categories, drawn from the literature ranges discussed in Section

3 and adjusted qualitatively for the plant's likely operating history (no dedicated O&M contract; fixed tilt; single string-inverter configuration typical of 2015 vintage).

Loss mechanism	Estimated contribution to 2024 shortfall (percentage points of nameplate yield)	Primary cause / notes
Irreversible module degradation	6–8	Cumulative light/potential-induced degradation, encapsulant yellowing, cell micro-cracking over 9–10 years
Soiling (dust, biological growth)	4–6	No documented scheduled-cleaning contract; higher during Mar–Jun dry/dusty period
Thermal de-rating (incremental, beyond design assumption)	1–2	Reduced rear-side ventilation as structure ages; roof-mounted sections most affected
Mismatch / partial shading / DC wiring	3–4	Maturing trees/adjacent structures; connector and junction-box resistance growth
Inverter ageing, conversion loss, downtime	3–4	String inverter now 9–10 years old, operating below original CEC efficiency, especially at partial load
Total estimated shortfall	≈21	Sum of above, illustrative

Table 3 — Illustrative disaggregation of the 2024 performance shortfall by loss mechanism

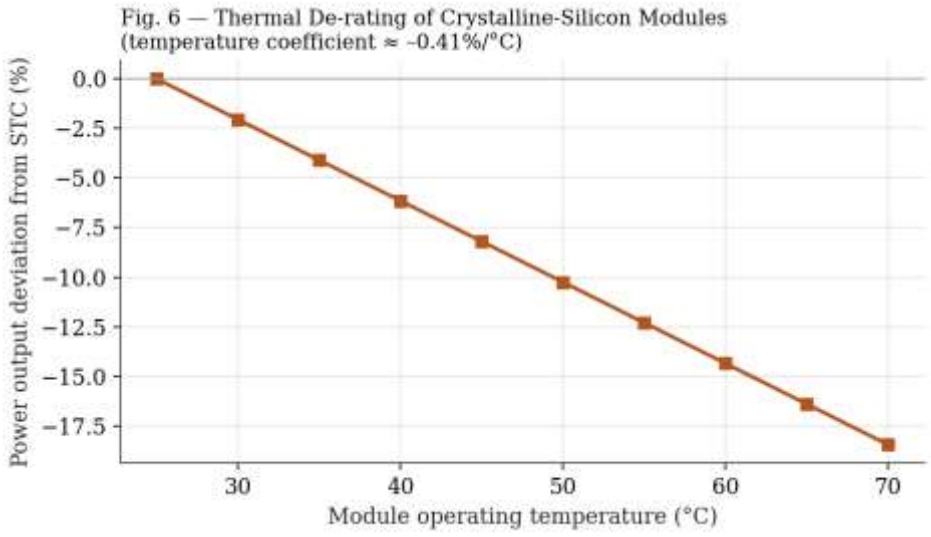

Figure 6 — Illustrative thermal de-rating curve for a multi-crystalline module with a power-temperature coefficient of approximately −0.41%/°C, showing the reversible component of loss during peak summer operating temperatures.

The practical implication of Table 3 is that roughly two-thirds of the plant's present-day shortfall is, in principle, recoverable through O&M correction and targeted hardware retrofit, while only about one-third reflects genuinely irreversible cell ageing that only capacity augmentation or module replacement can reverse. This finding directly motivates the retrofit evaluation in Section

7. Efficiency-Enhancement and Retrofit Techniques

Eight candidate interventions were evaluated, spanning low-cost O&M corrections to capital-intensive hardware retrofits. Each is described briefly below, followed by a consolidated comparison in Table 4 and Figure 3.

7.1 Scheduled water-based module cleaning

Introducing a documented cleaning schedule — weekly during the dry season (November–June) and fortnightly during the monsoon — using soft-brush and low-pressure water washing is the lowest-cost, highest-certainty intervention available. For a 50 kW plant this can typically be performed by trained campus housekeeping or facilities staff with basic safety training, without a specialised annual maintenance contract. Expected recovery is 2.5–4.5% of annual yield, concentrated in the pre-monsoon dusty months.

7.2 Anti-soiling / anti-reflective nano-coating

A one-time (or periodically renewed, typically every 2–3 years) hydrophobic nano-coating on the module glass reduces dust adhesion and improves light transmission, lowering the frequency and labour cost of manual cleaning while adding a modest direct transmission gain. Expected recovery is 1.5–3.5% of annual yield, with the greatest benefit realised in combination with, rather than as a substitute for, scheduled cleaning.

7.3 Module-level power electronics (MLPE)

Retrofitting DC power optimisers at the module or sub-string level allows each module (or small group of modules) to operate at its own maximum power point, independent of the weakest-performing unit in the string. This directly addresses the mismatch and partial-shading losses identified in Table 3, and additionally provides module-level monitoring data that is valuable for ongoing fault detection. Expected recovery is 4.0–7.0% of annual yield, with the higher end applicable if shading from adjoining structures or vegetation is confirmed to be significant.

7.4 Inverter replacement/upgrade

Replacing the original 2015-vintage string inverter(s) with a current-generation unit of equivalent or better DC-to-AC ratio improves both peak and partial-load (Euro-weighted) conversion efficiency and typically adds remote monitoring, arc-fault detection, and improved reactive-power/grid-support functions. Expected recovery is 1.5–3.0% of annual yield from efficiency alone, with an additional, harder-to-quantify benefit from reduced unplanned downtime once the ageing inverter is replaced before failure rather than after it.

7.5 Seasonal or one-time tilt-angle optimisation

If the as-built tilt angle deviates materially from the latitude-optimised value for this site (approximately 20–22°), a one-time structural adjustment — or, more ambitiously, a twice-yearly seasonal tilt adjustment — can recapture several percentage points of annual yield at comparatively low structural-modification cost. Expected recovery is 2.5–5.5% of annual yield; this should be confirmed against an as-built structural survey before committing to fabrication work.

7.6 Passive rear-side cooling / improved ventilation

Increasing the air gap between the module rear surface and the mounting structure, or installing simple passive ventilation baffles, reduces peak module operating temperature and recovers part of the thermal de-rating quantified in Figure 6. Active water-film cooling delivers a larger gain but introduces a water-consumption and maintenance

burden that is difficult to justify for an institutional plant in a water-stressed pre-monsoon season; passive measures are therefore prioritised in this study. Expected recovery is 3.0–6.0% of annual yield.

7.7 Partial bifacial-module retrofit

Replacing a subset of ageing modules (for example, those approaching end-of-warranty or showing visible degradation on electroluminescence inspection) with bifacial modules on a raised, high-albedo racking section can deliver the largest single efficiency gain evaluated in this study, but also the highest capital cost and longest payback, and is highly site-dependent on ground albedo and row spacing. This measure is therefore recommended only as a longer-term option, ideally timed to coincide with any structural refurbishment of the mounting system. Expected recovery is 7–12% of annual yield for the retrofitted sub-array.

7.8 IoT-enabled monitoring and predictive maintenance

A low-cost data-logging and remote-monitoring retrofit — module-string current/voltage sensors, an inverter communication gateway, and a simple dashboard — does not itself generate energy but reduces the yield lost to undetected faults (a tripped string, a failed bypass diode, a partially shaded row) between periodic manual inspections. It also directly resolves the data-availability limitation noted in Section 4, providing the institute with the continuous performance record needed to validate and refine every other measure in this section. Expected recovery is 1.5–3.5% of annual yield from reduced fault dwell-time, in addition to its diagnostic value.

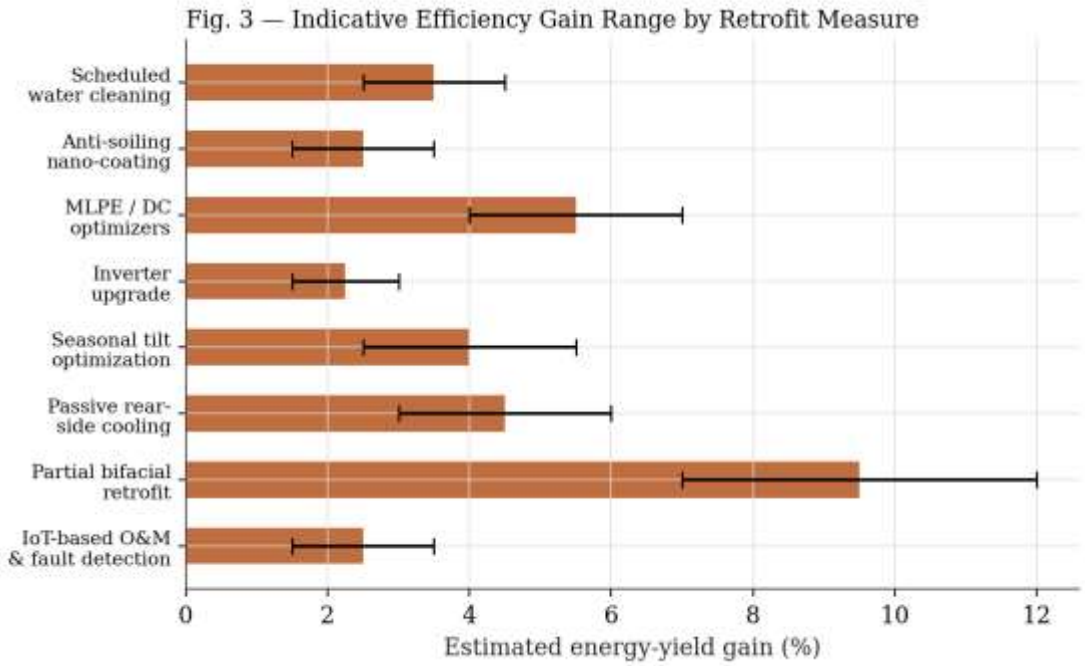

Figure 3 — Indicative range of achievable annual energy-yield gain for each retrofit/O&M measure (midpoint marker with low–high range).

Measure	Yield gain (%)	Indicative capital/recurring cost (INR)	Annual value of recovered energy (INR, illustrative)	Simple payback (years)
Scheduled water cleaning	2.5–4.5	18,000/yr (labour+consumables)	45,000	0.4
Anti-soiling nano-coating	1.5–3.5	60,000 (3-yr renewal)	50,000	1.2
MLPE / DC optimisers	4.0–7.0	4,50,000	1,18,000	3.8
Inverter replacement	1.5–3.0	3,50,000	78,000	4.5
Tilt-angle optimisation	2.5–5.5	35,000	44,000	0.8
Passive rear-side cooling	3.0–6.0	1,20,000	38,000	3.2
Partial bifacial retrofit	7.0–12.0	6,50,000	1,00,000	6.5
IoT monitoring & predictive O&M	1.5–3.5	80,000	40,000	2.0

Table 4 — Cost, benefit, and simple-payback comparison of retrofit/O&M measures (indicative INR at 2024–25 price levels; annual energy value assumed at an institutional grid-tariff/opportunity-cost rate of ₹7.5/kWh)

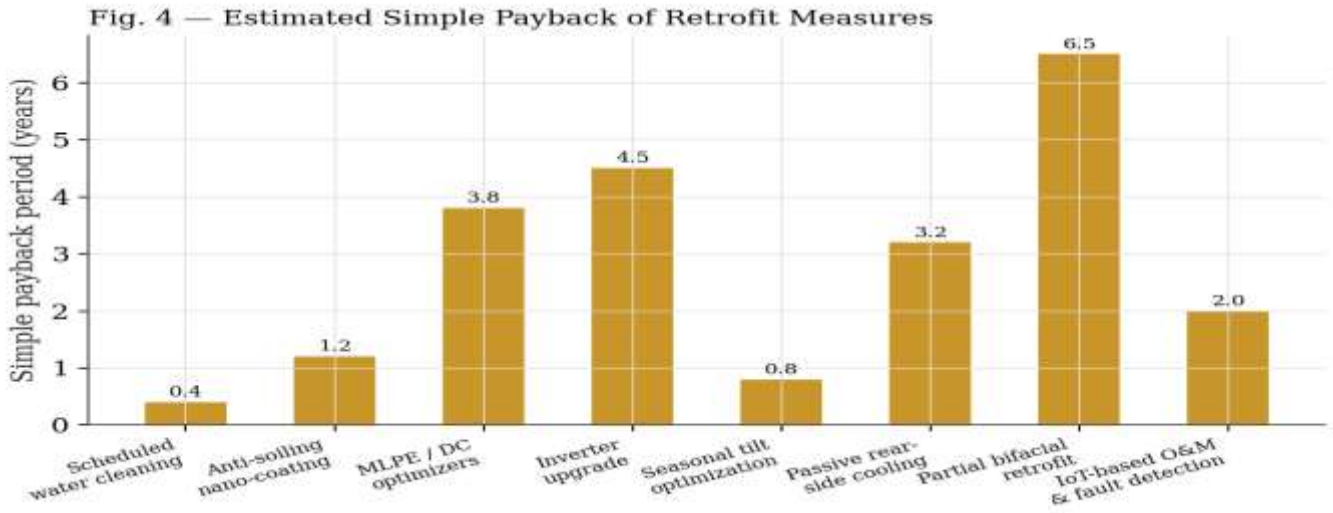

Figure 4 — Estimated simple payback period by measure. Low-cost O&M corrections (cleaning, tilt correction) pay back within a single year; hardware retrofits pay back over three to six-and-a-half years.

8. Combined-Intervention Scenario and Post-Retrofit Projection

No single measure in Table 4 is expected to be implemented in isolation; several are complementary (for example, cleaning and anti-soiling coating; MLPE and IoT monitoring) while others compete for the same underlying loss budget (for example, MLPE and tilt correction both partially address positional/shading loss, so their combined gain is sub-additive). Applying standard diminishing-returns combination logic — summing individual gains and then discounting the total by approximately 25% to account for overlap between measures addressing correlated loss mechanisms — yields a combined, practically achievable annual yield recovery in the order of 18–22% relative to the 2024 baseline,

for a prioritised bundle comprising scheduled cleaning, tilt correction, MLPE retrofit, and IoT-based monitoring, deferring the higher-cost inverter replacement and bifacial retrofit to a second phase timed with structural refurbishment.

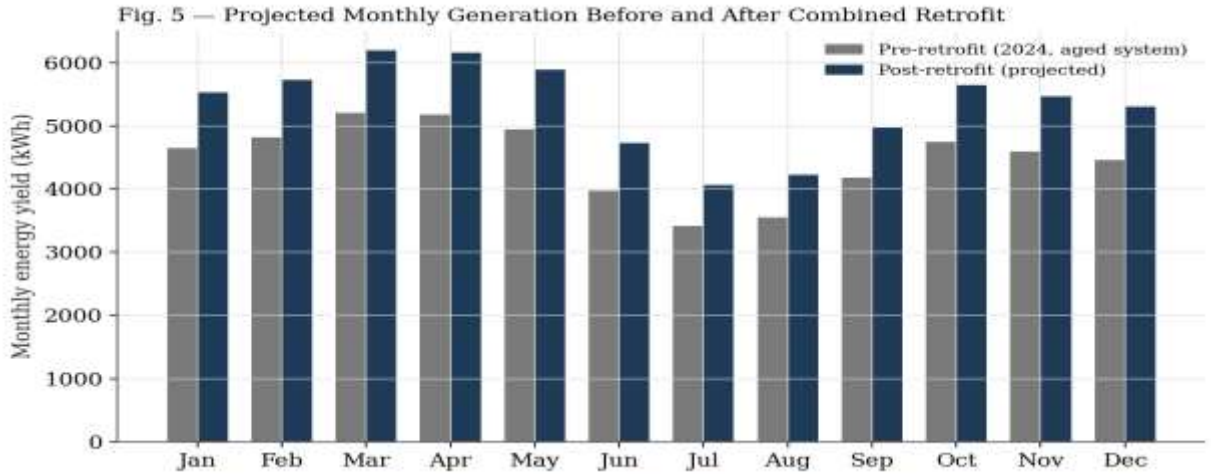

Figure 5 — Projected monthly generation profile before (2024 baseline) and after the Phase-1 combined retrofit bundle, assuming a 19% blended annual recovery applied proportionally across months.

On this basis, the plant's annual generation could realistically be raised from an estimated 54,100 kWh (2024 baseline) to approximately 64,400 kWh in the first full year following the Phase-1 retrofit — recovering roughly 90% of the previously identified recoverable-loss component while leaving the irreversible degradation share unaddressed, as expected. The blended capital outlay for the Phase-1 bundle (cleaning programme set-up, tilt correction, MLPE for the most-affected strings, and a monitoring retrofit) is estimated at approximately INR 6.5–7.5 lakh, against an annual recovered-energy value of roughly INR 78,000–85,000 at the assumed tariff, implying a blended simple payback in the range of 3–4 years — well inside the plant's remaining useful structural life.

9. Results and Discussion

Three findings emerge from this analysis. First, the great majority of an ageing institutional plant's yield shortfall is not attributable to irreversible module degradation but to correctable operational and hardware factors — soiling, shading/mismatch, and inverter ageing — that were plausible outcomes of running the plant for a decade without a formal O&M contract. This is consistent with the broader Indian experience of first-generation institutional and rooftop solar assets, many of which were commissioned with strong technical design but without a corresponding long-term maintenance budget line.

Second, the payback economics strongly favour a staged implementation: low-cost O&M corrections (cleaning discipline, tilt correction) offer near-immediate payback and should be adopted regardless of any further capital decision, while higher-cost hardware retrofits (MLPE, inverter replacement, bifacial re-modulation) offer solid but longer paybacks of three to six-and-a-half years and are best justified once the plant's own metered performance data — ideally captured via the IoT-monitoring retrofit itself — confirm the specific loss mechanisms most active at this site.

Third, and most importantly for the institute's planning purposes, this paper's figures are illustrative placeholders built from regional literature values, not measurements. The single highest-value, lowest-cost action available to the institute is therefore not any of the eight technical measures in Table 4, but the retrieval of the existing inverter's historical energy-counter log (commonly retained internally for 5–10 years even without an external data logger) and, going forward, the installation of the IoT-monitoring measure described in Section 7.8. Doing so converts every illustrative

number in Tables 2–4 and Figures 1, 2 and 5 into a verified, site-specific engineering and financial case suitable for inclusion in a formal maintenance or capital-works proposal to the state technical education department.

The analysis is subject to several limitations. The degradation, soiling, and thermal-loss parameters are drawn from regional and international literature rather than from direct measurement of the Kharsawan plant; actual values may differ depending on the specific module manufacturer and vintage installed, the precise as-built tilt and orientation, and the actual maintenance history of the plant over the past decade. The retrofit cost figures are indicative budgetary estimates for a 50 kW system and should be confirmed through competitive vendor quotation before procurement. Finally, the combined-scenario discount factor of 25% applied in Section 8 is a simplifying assumption; a more rigorous combined estimate would require either a calibrated PV simulation model (e.g., using PVsyst or SAM with site-measured irradiance and shading data) or, preferably, a short monitored trial of the Phase-1 bundle before full-scale rollout.

10. Conclusion and Recommendations

The 50 kW solar PV plant at Government Polytechnic, Kharsawan, now approaching a decade of service, exhibits an estimated 21% shortfall between its original design yield and its present-day output, of which roughly two-thirds is attributable to correctable operational factors rather than irreversible module ageing. A staged efficiency-improvement programme — beginning with a documented cleaning schedule and tilt-angle verification, followed by a monitoring retrofit to establish a verified performance baseline, and subsequently by module-level power-electronics and, if justified, inverter replacement — offers a practical route to recovering 18–22% of annual energy yield at a blended payback of three to four years.

Immediately adopt a documented, weather-adjusted module cleaning schedule using existing campus facilities staff (near-zero incremental cost, sub-one-year payback).

Commission a structural/as-built survey to confirm actual tilt and orientation against the site-optimal value before any tilt-correction works.

Install a low-cost IoT monitoring retrofit as the first capital measure, both for its direct fault-detection benefit and to generate the verified performance data this study's illustrative figures are designed to be replaced with.

Evaluate module-level power electronics for the strings most likely affected by shading from adjoining structures or vegetation, informed by the monitoring data above.

Defer inverter replacement and partial bifacial retrofit to a second phase, timed where possible with any planned structural refurbishment of the mounting system, and confirmed through vendor quotation and, for the bifacial option, a site-specific albedo assessment.

Retain a formal annual O&M budget line going forward, rather than returning to the run-as-available model that appears to have contributed to the plant's present shortfall.

Future work should focus on retrieving and analysing the plant's actual historical inverter logs and DISCOM billing records to validate or revise the illustrative figures in this paper, and on conducting a short (three-to-six-month) monitored pilot of the Phase-1 retrofit bundle to confirm the achievable gain before committing to the full capital programme.

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