

A 180-kWp Grid-Connected Rooftop PV System for Energy Security in Higher-Education Institutions: Long-Term Performance and Financial Robustness at Shivaji University, Kolhapur

Amit C. Kamble¹, Himmat T. Jadhav²

¹Ph.D. Research Scholar, Department of Technology, Shivaji University, Kolhapur, India

²Faculty of Science and Technology, SNDT Women's University, Mumbai, India

Abstract- Energy security and tariff volatility are growing concerns for Indian higher-education institutions (HEIs) due to rising digital infrastructure, cooling loads, and escalating electricity prices. This paper presents a multi-year, bill-validated assessment of a 180.18 kWp grid-connected rooftop PV system installed at Shivaji University, Kolhapur (SUK). Beyond reporting measured performance (average generation $\approx 283,824$ kWh/yr; CUF $\approx 18\%$), the study introduces a Performance Stability Index (PSI) and a Tariff Resilience Index (TRI) to quantify interannual energy stability and financial robustness under adverse tariff scenarios. A 25-year discounted-cash-flow model, incorporating real tariff evolution, yields an IRR of 18.4%, NPV of about INR 517 lakh, and payback of ~ 5.3 years. Annual CO₂ avoidance is estimated at ~ 233 tCO₂/yr using the CEA grid factor. A benchmarking framework situates the system against Indian HEI PV case studies, and a replication pathway is outlined for campus-scale deployment. The results demonstrate that rooftop PV can significantly enhance HEI energy security while supporting national solar and NEP-2020 sustainability goals.

Keywords- Energy security, rooftop solar photovoltaics, higher-education institutions, techno-economic analysis, carbon mitigation.

I. INTRODUCTION

India's higher-education institutions (HEIs) must balance rapidly increasing electricity demand from digitalization, laboratories, and air-conditioning with the need for affordable, reliable, and low-carbon power. In Maharashtra, commercial tariffs have risen from roughly INR 7.2 to INR 10.03/kWh between FY 2017–18 and FY 2024–25, directly affecting university operating budgets.

Rooftop PV deployment on Indian campuses has grown in response, yet important gaps remain:

- Limited availability of long-term, bill-validated performance datasets (most studies rely on 1–2 years of monitoring or purely simulated data).
- Limited focus on energy security and tariff-hedging benefits, despite rapid tariff escalation.
- Sparse use of systematic sensitivity analysis to test financial robustness to CUF, degradation, and tariff variations.

- Minimal cross-comparison and benchmarking of PV performance across Indian HEIs.
- Lack of practical replication frameworks tailored to HEIs. This paper addresses these gaps using the 180.18 kWp rooftop PV system commissioned in 2018 at Shivaji University, Kolhapur (SUK). The work is consistent with the National Solar Mission, UGC Green-Campus guidelines, and the broader Atmanirbhar Bharat energy self-reliance agenda.

A. Research Questions

The study is guided by the following questions:

1. What is the long-term technical performance (CUF, specific yield, stability) of the rooftop PV system in an HEI context?
2. How financially viable is the system over a 25-year horizon under the observed tariff trajectory?
3. How resilient are investment returns to changes in CUF, degradation rate, and tariff assumptions?

4. What are the quantified carbon-mitigation benefits?
5. How does the system compare with published Indian HEI PV benchmarks?

B. Contributions

The main contributions are:

- An eight-year, bill-validated PV dataset (2018–2025) for an Indian HEI—rarely reported in the literature.
- Two new metrics:
 1. Performance Stability Index (PSI) to quantify inter-annual variability of PV energy,
 2. Tariff Resilience Index (TRI) to capture reduction in IRR under conservative tariff scenarios.
- A performance benchmarking framework spanning Indian rooftop PV studies with CUF/PR comparison.
- A sensitivity-based techno-economic analysis (CAPEX, CUF, tariff, degradation) highlighting financial robustness.
- A concise replication framework to support strategic rooftop PV deployment in HEIs.

TABLE I: List of Abbreviations and Notations

Symbol/Abbrev.	Definition
HEI	Higher-Education Institution
PV	Photovoltaic
CUF (%)	Capacity Utilization Factor: $E_{AC} P_{inst} \times 8760 \times 100$
PR (%)	Performance Ratio: $Y_f Y_R$
Y_{spec}	Specific Yield (kWh/kWp · yr)
E_{AC}	Annual AC Energy Output (kWh)
P_{inst}	Installed DC Capacity (kWp)
NPV	Net Present Value (lakh)
IRR (%)	Internal Rate of Return
O&M	Operations and Maintenance
CAPEX	Capital Expenditure (crore)
DCF	Discounted Cash Flow
LCOE	Levelized Cost of Energy (/kWh)
CO ₂ (t)	Carbon dioxide avoided (tons)
EF _{grid}	Grid emission factor (0.82 kg CO ₂ /kWh)

Abbreviations and key notations are summarized in Table I.

II. RELATED WORK

Energy-audit studies in Indian educational institutions consistently report that lighting and fans dominate electricity consumption, often accounting for 70–75% of building loads [4], [6]. While a large body of work addresses conservation opportunities via efficient equipment and operational controls,

long-term rooftop PV performance evaluations on campuses remain relatively scarce.

Most rooftop PV case studies in India report short monitoring windows or rely heavily on simulation. PR values typically lie in the 70–80% range, with CUF around 13–16% for small and medium systems [5], [7], [8], [12]. Net-metered HEI systems have been evaluated primarily for payback and IRR using short-term yield estimates [13]. In contrast, this work provides an eight-year, bill-validated dataset and introduces PSI/TRI metrics combined with tariff- and CUF-based sensitivity analysis. Comparative PR/CUF benchmarks are summarised in Table VII.

III. SITE AND SYSTEM DESCRIPTION

A. Campus and Rooftops

The 180.18 kWp grid-connected rooftop PV system at Shivaji University, Kolhapur, is deployed on two buildings: the Main Administrative Building (100.80 kWp, 320 modules) and the Chemistry Building (79.38 kWp, 252 modules), totalling 572 modules and interconnected to the campus grid via net metering.

B. Array Configuration

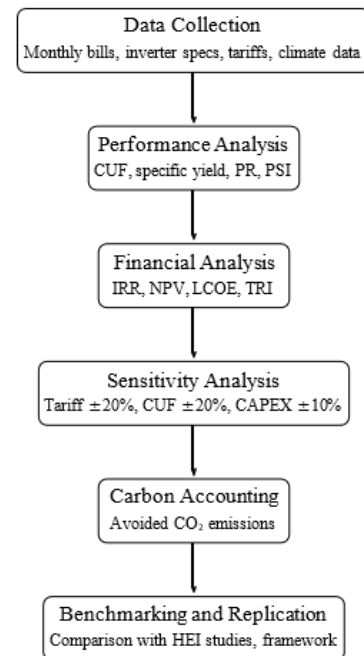


Fig. 1: Methodology flowchart for performance, financial, and carbon assessment.

Modules are grouped into inverter-centric strings of 20–21 modules, sized to respect inverter DC-voltage windows under expected temperature conditions and rooftop layout constraints. The Main Administrative Building hosts four Fronius Eco 25.0-3-S inverters, and the Chemistry Building hosts three Fronius Eco 27.0-3-S inverters.

C. Modules and Inverters

The plant uses Waaree polycrystalline 315 Wp (72-cell) modules with efficiency of about 16.23%. Key module parameters are: VOC ≈ 46.4 V, ISC ≈ 9 A, Vmp ≈ 37.5 V, and Imp ≈ 8.4 A.

The inverters provide a DC input window of roughly 580–1000 V, with a single MPP tracker and six DC inputs. Nominal AC ratings are 25–27 kW, with European efficiencies near 98% and IP66 outdoor enclosures.

D. Protection and Compliance

Grid-interactive functions include DC insulation monitoring, reverse-polarity protection, DC disconnects, and string fusing. Inverters support voltage/frequency ride-through and communications via Ethernet/Wi-Fi, Modbus, and RS422/RS485. Compliance is maintained with IEC 62109, IEC 61727, IEC 62116, and VDE AR-N 4105. Technical specifications are summarized in Table II.

IV. METHODOLOGY AND DATA

A. Overview

The methodology (Fig. 1) combines measured generation and tariff data with standard PV performance metrics, discounted-cash-flow (DCF) analysis, sensitivity analysis, and carbon accounting. Methodological assumptions are summarized in Table III.

TABLE II: Technical Specifications of the 180.18 kWp PV System

Item	Main Admin	Chemistry	Notes
DC Capacity (kWp)	100.80	79.38	Total = 180.18
Modules (# × Wp)	320 × 315	252 × 315	572 total
Inverters (qty, model)	4 × 25.0	3 × 27.0 kW	Fronius Eco, IP66

	kW		
Strings per inverter	2–3	2–3	20 (Admin) / 21 (Chem) modules
MPP voltage window (DC)	580–850 V		Overall range 580–1000 V
Communications	Ethernet/Wi-Fi, Modbus, RS422/485		Solar.web + JSON API

TABLE III: Methodological Notes Used in the Study

Topic	Notes
Performance metrics	CUF, PR and specific yield as per IEC 61724 [14].
Financial modelling	Discount rate 8%; tariffs as billed; O&M = INR 1 lakh/yr; degradation 0.8%/yr; optional inverter replacement.
Carbon factor	CO ₂ reductions based on 0.82 kg/kWh with a ±10% sensitivity check.

B. Data Sources

PV generation (2018–2025): Monthly exported/offset energy values were compiled from university electricity bills and aggregated to annual totals for performance and financial evaluation.

Electricity tariffs: Effective tariffs (INR/kWh) were derived from annual billing records, ranging from 7.20 INR/kWh (2017–18) to 10.03 INR/kWh (2024–25). The tariff schedule used in financial analysis is given in Table IV.

Costs: The installed plant cost (CAPEX) was INR 1.05 crore; annual O&M was assumed at INR 1 lakh, consistent with project documentation.

Emission factor: Carbon accounting adopts the CEA grid emission factor of 0.82 kg CO₂/kWh [1].

C. Performance Indicators

For installed DC capacity Pinst (kWp) and annual AC energy EAC,t (kWh) in year t:

Specific Yield:

$$Y_{spec,t} = \frac{E_{AC,t}}{P_{inst}} \quad [\text{kWh/kWp} \cdot \text{yr}]. \quad (1)$$

For SUK, the long-term average specific yield is ~1575 kWh/kWp·yr.

b) Capacity Utilization Factor (CUF):

$$CUF_t = \frac{E_{AC,t}}{P_{inst} \times 8760} \times 100\%. \quad (2)$$

The average CUF is approximately 18%.

c) **Performance Ratio (PR):** With final yield Y_F = EAC_t/P_{inst} and reference yield Y_R derived from annual

$$PR = \frac{Y_F}{Y_R} \cdot \text{irradiation,}$$

In the absence of on-site irradiance measurements, PR is estimated using satellite-based PVGIS data for Kolhapur [10], as detailed in Sec. IV-I.

D. Financial Analysis

A 25-year DCF model is constructed for $t = 0, \dots, 25$.

a) **Energy and Savings:** For base-year energy E_0 and degradation rate d :

$$E_t = E_0(1-d)^{t-1}, \quad S_t = E_t \times T_t, \quad (4)$$

where T_t is the effective tariff in year t (INR/kWh).

Net Cash Flow: With annual O&M cost O_t

$$CF_t = S_t - O_t - R_t, \quad CF_0 = -CAPEX. \quad (5)$$

c) **NPV, IRR, and Payback:** For discount rate r :

IRR is the rate r at which $NPV = 0$. Simple payback is the smallest t for which $\sum_{\tau=1}^t CF_\tau \geq 0$. Annual and cumulative cash flows are illustrated in Fig. 4.

TABLE IV: Effective Tariff Schedule (INR/kWh)

FY	Tariff	FY	Tariff
2017–18	7.20	2021–22	7.74
2018–19	7.70	2022–23	7.74
2019–20	7.90	2023–24	9.53
2020–21	7.74	2024–25	10.03

A. Tariff Resilience Index (TRI)

The Tariff Resilience Index (TRI) captures the sensitivity of IRR to lower tariffs:

$$TRI = \frac{IRR_{base} - IRR_{lowTariff}}{IRR_{base}}$$

(9)

IRR_{base}

where IRR_{base} is computed for the observed tariff path and $IRR_{lowTariff}$ for a reduced-tariff scenario.

For example, when the effective tariff is reduced from 10.03 INR/kWh to 7.0 INR/kWh:

$$IRR_{base} \approx 18.4\%, \quad IRR_{lowTariff} \approx 14.6\%,$$

giving

$$TRI \approx 0.206,$$

indicating robust returns even under conservative tariff assumptions.

I. PR Estimation from PVGIS

Using PVGIS for Kolhapur, the global horizontal irradiation (GHI) is approximately:

$$GHI \approx 5.2 \text{ kWh/m}^2/\text{day}.$$

This corresponds to an annual reference yield:

$$Y_R \approx 1898 \text{ kWh/kWp} \cdot \text{yr.} \quad (10)$$

10) With measured specific yield

$$Y_{meas} \approx 1575 \text{ kWh/kWp} \cdot \text{yr},$$

the PR is estimated as:

$$PR \approx \frac{Y_{meas}}{Y_R} \approx 0.83. \quad (11)$$

This is higher than the typical 0.70–0.80 range reported for Indian rooftop systems [12], indicating strong system health and effective design and O&M.

V. RESULTS

A. Generation and Performance

Annual billed data (2018–2025) show stable output of $E_{yr} \approx 283,824 \text{ kWh}$

from the 180.18 kWp system, corresponding to

$$Y_{spec} \approx 1575 \text{ kWh/kWp} \cdot \text{yr}, \quad CUF \approx 18\%.$$

Compared with a 5 kWp rooftop system in Manipur reporting $CUF \approx 14.3\%$ [5], the SUK system shows higher utilisation. Seasonal generation trends for selected years are shown in Fig. 5, illustrating monsoon-related dips and strong pre-/post-monsoon output.

Metric	Value
Installed capacity	180.18 kWp
CAPEX	INR 1.05 crore
Annual O&M	INR 1.0 lakh
Average generation	283,824 kWh/yr
Annual savings	~INR 19.9 lakh
Net annual benefit	~INR 18.9 lakh
Simple payback	~5.3 years
IRR (25 yrs)	~18.4%
NPV (8%)	~INR 517 lakh
Break-even year	~Year 6
IRR range (sensitivity)	~10–30%

TABLE VI: CO₂ Mitigation Based on CEA Factor

Item	Value
Annual PV energy	283,824 kWh
Annual CO ₂ avoided	~233 tCO ₂ /yr
25-year cumulative	~5,825 tCO ₂
Emission factor sensitivity	±10% EF check

B. Economics

Using the effective tariffs in Table IV and measured generation:

- Average annual savings: ~INR 19.9 lakh.
- Net annual benefit (after O&M): ~INR 18.9 lakh.
- Simple payback: ~5.3 years, with break-even around Year 6.
- IRR over 25 years: ~18.4%.
- NPV at 8% discount: ~INR 517 lakh.

A summary is provided in Table V. Annual and cumulative cash flows are visualised in Fig. 4. IRR sensitivity to CUF and tariff is shown in Figs. 2 and 3, where IRR spans roughly 10–30% across realistic parameter ranges.

C. Carbon Mitigation

With the CEA grid factor of 0.82 kg CO₂/kWh, avoided emissions are:

$$CO_2^{\text{annual}} \approx 233 \text{ tCO}_2/\text{yr}, \quad CO_2^{25\text{yr}} \approx 5,825 \text{ tCO}_2$$

as summarised in Table VI. This underlines the dual financial and environmental benefits of the project.

D. Benchmarking

Table VII compares SUK performance with selected Indian rooftop PV case studies. The SUK CUF of about 18% and estimated PR of 83% place the system at the upper end of reported performance for institutional rooftops.

VI. DISCUSSION

A. Relevance for HEIs

The SUK plant operates in a typical HEI load environment dominated by daytime teaching, laboratory, and administrative activities. The strong alignment between PV generation and daytime demand yields high self-consumption and effective tariff hedging. The CUF of ~18% compares favourably with smaller HEI plants (CUF ~13–15%), indicating that appropriate design, stringing, and O&M can deliver robust long-term performance.

TABLE VII: Benchmarking Against Indian Rooftop PV Literature

Case/Study	Size (kWp)	PR (%)	CUF (%)	Notes
This work: SUK campus	180.18	~83	~18	8-year bill-validated dataset (2018–2025)
Imphal, Manipur [5]	5	~74.4	~14.3	24-month monitored; moderate climate
Gujarat HEI [8]	120	72–78	15–16	Short-term monitoring + modelling
Tripura campus [6]	80	70–75	13–15	Simulated plus limited measurements
Institutional rooftop [7]	100	70–80	13–16	Financial viability focus

Escalating tariffs (7.20 to 10.03 INR/kWh over seven years) strengthen project economics: the observed IRR of 18.4% and NPV of about INR 517 lakh remain attractive even under conservative tariff assumptions, as reflected in the TRI value.

B. Positioning with Efficiency Literature

Energy-audit studies in HEIs show that fans and lighting often contribute more than two-thirds of electricity use [4], [6]. When efficiency measures (LEDs, efficient fans, AC set-point optimisation) are combined with rooftop PV, campuses can simultaneously reduce baseload, increase PV self-consumption, and improve financial returns. The SUK case illustrates how supply-side PV can complement demand-side efficiency to achieve broader energy-security goals.

C. Replication Notes for HEIs

Key lessons for replication include:

- Array and inverter design: Maintain consistent orientation and tilt per inverter; size strings to stay within MPP windows across seasonal temperature extremes.
- Segmentation: Distribute capacity across multiple rooftops and inverters for ease of isolation, phased expansion, and O&M access.
- Financial evaluation: Include CUF–tariff IRR matrices, explicit degradation assumptions, and scenario analysis for tariffs and CAPEX.
- Monitoring: Use inverters with integrated data logging, IP66 enclosures, and remote fault alerts to minimise downtime and track PR/CUF in near real-time.

VII. LIMITATIONS AND FUTURE WORK

A. Data and Measurement

The analysis relies on billed AC energy; on-site plane-of-array irradiance and back-of-module temperature were not recorded. Future plants should incorporate pyranometers and temperature sensors to enable detailed PR and loss analysis, including thermal, soiling, and mismatch losses. Soiling was not explicitly quantified; deploying clean/dirty reference strings or I-V tracing would help optimise cleaning schedules.

B. Economic Modelling

Inverter replacements were treated parametrically. More detailed models can schedule explicit replacement costs R_t in year t :

$$PV(R) = \frac{r^N}{(1+r)^{t_r}} \quad (12)$$

LCOE can also be computed as:

$$LCOE = \frac{CAPEX + \sum_{t=1}^N O_t + R_t(1+r)^t}{\sum_{t=1}^N E_t(1+r)^t} \text{ [INR/kWh]} \quad (13)$$

Beyond deterministic CUF–tariff grids, Monte Carlo analysis over $\{d, T_t, E_0, g\}$ could quantify IRR/NPV distributions and value-at-risk.

C. System Integration and EMS

Outage and curtailment logs were not systematically correlated with energy shortfalls. Integration with a campus energy-management system (EMS) could support demand response (e.g., scheduling chillers, pumps, and EV charging into solar windows) and enable more granular resilience analysis. Future work can evaluate storage options (batteries or thermal storage) for peak-shaving, TOU arbitrage, and ride-through services.

VIII. CONCLUSIONS

This paper presented a long-term performance and financial assessment of a 180.18 kWp grid-connected rooftop PV system installed at Shivaji University, Kolhapur. Over 2018–2025, the plant has delivered stable generation of ~283,824 kWh/yr, corresponding to a specific yield of ~1575 kWh/kWp·yr and CUF of ~18%, validated against utility bills.

Using actual tariff evolution, the 25-year DCF analysis yields an IRR of about 18.4%, NPV of roughly INR 517 lakh at an 8% discount rate, and a simple payback of ~5.3 years. The project reaches cumulative cash-flow breakeven around Year 6. Estimated CO₂ reductions are ~233 tCO₂/yr and ~5,825 tCO₂ over 25 years.

The proposed Performance Stability Index (PSI) confirms highly stable interannual generation (PSI ≈ 0.95), while the Tariff Resilience Index (TRI) shows that IRR remains in the double digits even under conservative tariff scenarios. Benchmarking indicates that SUK performance is at the upper end of reported Indian institutional rooftops in terms of CUF and PR.

Overall, the SUK rooftop PV system demonstrates that HEIs can achieve verifiable energy savings, strong financial returns, and significant carbon mitigation through well-designed, well-operated rooftop PV assets. The metrics and replication notes presented here can support HEIs in scaling rooftop PV as a practical pathway to energy security and decarbonisation.

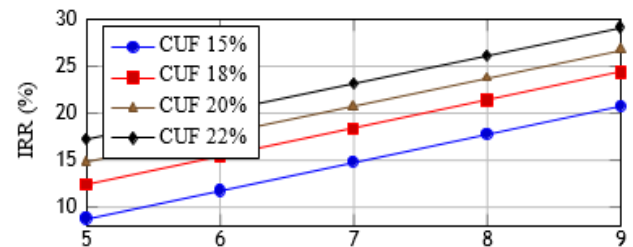


Fig. 2: IRR sensitivity curves across tariff and CUF.

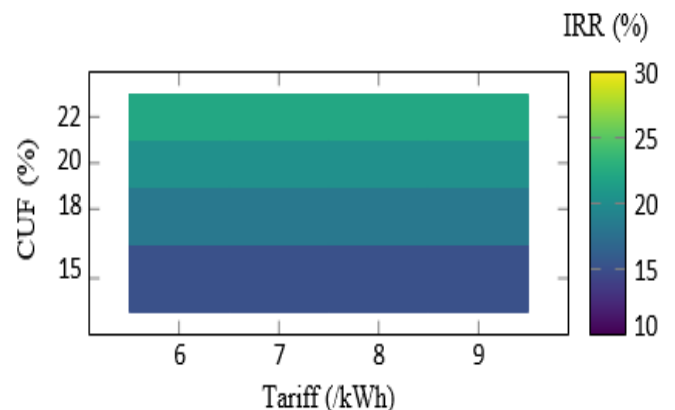


Fig. 3: IRR sensitivity heatmap across tariff and CUF

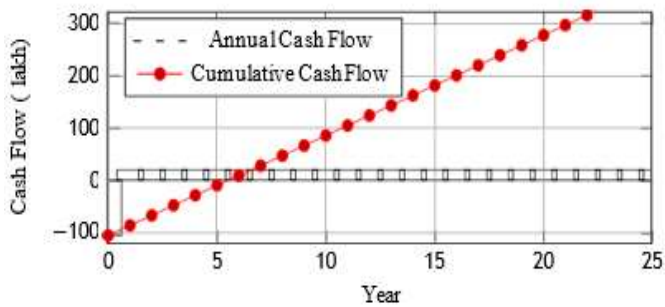


Fig. 4: Annual (bars) and cumulative (line) cash flows over 25 years

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