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From Load Profiling to Resilient Solar Availability: An Engineering Management Framework for Optimizing Distributed PV Systems in U.S. Facilities

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Abstract- Distributed photovoltaic (PV) systems have become central to decarbonisation, facility resilience, and electricity-cost management in the United States. Yet many facility-scale installations underperform because design decisions are made around nominal capacity rather than operational load shape, inverter availability, thermal behaviour, commissioning quality, maintenance discipline, and lifecycle risk. This paper develops an engineering-management framework that links load profiling, component selection, commissioning protocols, preventive maintenance, performance validation, documentation, and lifecycle cost-risk analysis into a single operating model for resilient solar availability in U.S. facilities. The paper uses secondary data from the Kaggle Solar Power Generation Data dataset, which contains inverter-level PV generation and weather-sensor data collected at two solar plants over a 34-day period, and triangulates those data with published PV reliability, O&M, and performance literature. The analysis shows that PV availability is not merely a generation problem; it is a management-system problem involving demand forecasting, conversion efficiency, module-temperature exposure, inverter variation, sensor quality, maintenance scheduling, and evidence-based documentation. The Kaggle-based evidence indicates that daily yield may appear similar across plants while DC-to-AC conversion performance, cumulative yield, and maintenance-event signatures differ materially. Published analysis of the same dataset reports mean daily yields of approximately 3,295.97 kWh and 3,294.89 kWh for Plants 1 and 2, respectively, while also identifying strong correlations between module temperature and ambient temperature, and between module temperature and irradiation. The proposed framework converts these findings into a practical facility protocol: profile the load before sizing, select components against operating conditions, commission against measurable acceptance criteria, maintain based on risk and performance evidence, validate availability continuously, and document lifecycle decisions for auditability. The study contributes an applied model for engineers, facility managers, energy consultants, and public-interest energy practitioners seeking to improve solar reliability, resilience, and return on investment in distributed PV systems.

Keywords: Distributed Photovoltaic Systems, Load Profiling, Solar PV Availability, Preventive Maintenance, Commissioning; Engineering Management, Energy Resilience, Lifecycle Cost-Risk Analysis, Facility Energy Optimization

I. INTRODUCTION

Solar photovoltaic systems have moved from marginal renewable-energy installations to core assets in facility strategy. In the United States, utility-scale solar power generation reached 296,000 GWh in 2025, a 34 percent increase from 2024, while small-scale solar generation reached 93,000 GWh in the same year (EIA, 2026a). Developers also planned 43.4 GW of new utility-scale solar capacity for 2026, which illustrates that the engineering challenge has shifted from whether PV will grow to whether PV assets will be operated with sufficient reliability, maintainability, and economic discipline (EIA, 2026b). This shift is especially important for hospitals, universities, public facilities, border infrastructure, manufacturing sites, sports facilities, warehouses, commercial buildings, and mixed-use campuses whose energy requirements are driven by

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both predictable base load and event-specific demand peaks.

The technical promise of distributed PV is clear: it can reduce grid dependence, improve resilience, support sustainability goals, and provide a hedge against electricity-price volatility. However, nominal PV capacity does not automatically translate into useful facility availability. A facility may install adequate DC capacity and still experience weak outcomes if the system is mis-sized against the actual load profile, if inverters are mismatched or poorly monitored, if thermal derating is ignored, if commissioning is treated as a sign-off exercise rather than a measured acceptance process, or if preventive maintenance is not tied to operating evidence. NREL and partner laboratories emphasise that PV operations and maintenance should be structured to reduce cost, improve effectiveness, and protect long-term system performance (NREL et al., 2018).

This paper argues that facility-scale solar optimisation should be treated as an engineering-management problem rather than a narrow equipment-selection problem. The first managerial question is not simply how many panels can fit on a roof or land parcel. The first question is how the facility consumes energy hour by hour, which loads are critical, which loads can shift, what reliability standard is required, what conversion losses are acceptable, how temperature affects output, how spares and maintenance are managed, and how performance evidence is preserved. That orientation is consistent with Godsave Archford Sajanga's professional trajectory in electronic engineering, solar PV design and commissioning, energy demand analysis, preventive maintenance, system documentation, power distribution, automation, and load-critical infrastructure operations.

The article therefore proposes a framework titled Load Profile to Resilient Solar Availability (LPRSA). The framework links seven management stages: demand/load profiling, site and component selection, system architecture, commissioning and readiness validation, preventive maintenance, performance monitoring, and lifecycle cost-risk governance. The purpose is to translate PV data into actionable decisions for U.S. facilities that need reliable clean power rather than symbolic installations.

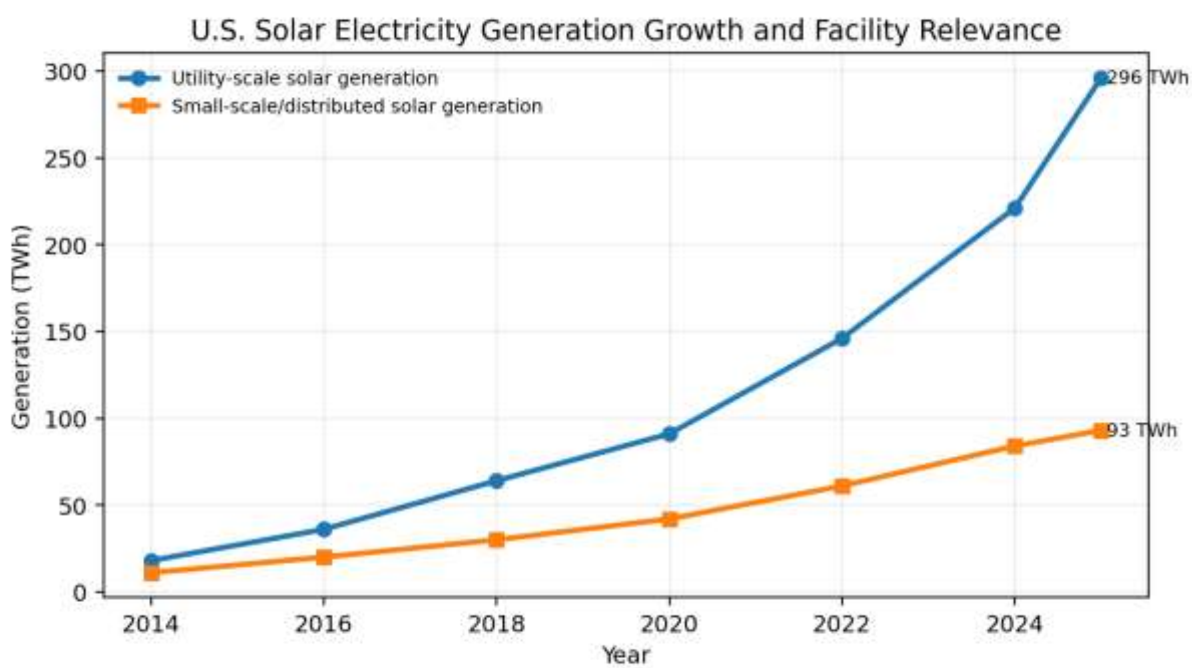

Figure 1. U.S. solar generation growth and the facility-level need for availability-focused PV engineering. Source: author visualisation using EIA data cited in text.

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II. PROBLEM STATEMENT AND RESEARCH OBJECTIVES

Despite the expansion of solar PV capacity, many distributed systems remain vulnerable to availability losses, poor performance-ratio interpretation, undocumented commissioning defects, under-specified inverter monitoring, component mismatch, thermal stress, delayed maintenance, and insufficient integration with facility load patterns. These weaknesses are costly because facility-scale PV systems are not isolated energy devices; they are part of a broader operational architecture that includes critical loads, safety obligations, equipment uptime, stakeholder expectations, utility interconnection, storage options, and financial payback.

The central research problem addressed in this article is therefore: How can engineering managers optimise distributed PV systems in U.S. facilities by connecting load profiling, component selection, commissioning, preventive maintenance, performance validation, documentation, and lifecycle cost-risk analysis into a repeatable framework for resilient solar availability?

The research objectives are:

- To examine the relationship between facility load profiling and PV availability planning.
- To synthesise empirical evidence from the Kaggle Solar Power Generation Data dataset and relevant PV performance literature.
- To develop measurable operating indicators for PV commissioning, maintenance, and performance validation.
- To present heat maps and decision tables that translate solar data into engineering-management actions.
- To propose an implementation framework suitable for U.S. facilities seeking reliable, auditable, and economically defensible distributed PV systems.

III. LITERATURE REVIEW

3.1 Distributed PV as a facility resilience asset

Distributed PV systems are increasingly valued not only for carbon reduction but also for energy resilience. The U.S. Large-Scale Solar Photovoltaic Database documents the expansion of large PV facilities and provides a public foundation for operational impact analyses, environmental interaction studies, and PV infrastructure assessment (Fujita et al., 2026). At facility scale, however, the management question is more granular: how can a specific site convert available solar resource into reliable operational value?

PV technologies convert solar radiation into useful electricity, but practical availability depends on irradiance, temperature, component performance, inverter operation, monitoring quality, maintenance response, and load integration (DOE, 2022). The International Energy Agency observes that solar PV has become one of the largest contributors to renewable electricity growth globally, while the IEA PVPS Task 13 programme emphasises technical performance, durability, reliability, and recommendations for improving electrical and economic output across climates (IEA, 2024; IEA PVPS, 2026).

3.2 Availability, performance ratio and energy ratio

Availability, performance ratio and energy ratio are useful PV performance metrics, but they must be interpreted carefully. The U.S. Department of Energy identifies availability as actual measured hours of production divided by modelled hours of production, while performance ratio and energy ratio provide additional ways to judge conversion of solar resource into useful output (DOE, 2022). Klise, Stein and Riley (2017) warn that availability is often misapplied when PV assets are evaluated using traditional power-plant language without recognising the particularities of solar intermittency and modelled production.

For facility engineering managers, the implication is that a PV system should not be judged only by installed capacity, nameplate rating, or a monthly bill comparison. The system should be monitored against a validated production baseline, load-critical operating windows, inverter-level performance, weather-adjusted output, outage signatures, and maintenance response time. This makes data governance and documentation essential parts of energy performance.

3.3 Preventive maintenance and reliability management

PV O&M literature increasingly treats maintenance as a reliability and asset-management function rather than a reactive repair function. NREL's best-practices guidance recommends planned maintenance, systematic inspection, documentation, safety processes, performance monitoring, and cost-effective O&M methods for PV and storage systems (NREL et al., 2018). Sonawane et al. (2023) further show that fault-tree analysis can identify component-level risks that reduce PV reliability and lifetime. Reliability, availability and maintainability analysis has also been framed as directly linked to PV system performance (Torres Navarro, 2025).

Preventive maintenance is especially important for distributed PV in public and commercial facilities because downtime has wider consequences than energy loss. A system that underperforms during business hours can increase grid draw, reduce the credibility of sustainability targets, weaken resilience planning, and distort lifecycle financial assumptions. Maintenance should therefore be scheduled and prioritised using evidence: inverter behaviour, thermal patterns, cleaning needs, abnormal zero-output periods, sensor anomalies, and repeated alarms.

3.4 Forecasting, data analytics and smart-grid optimisation

Solar PV output is weather-dependent, time-dependent, and component-dependent. Forecasting literature demonstrates that irradiance, temperature, historical output, and weather data can be used to improve short-term and day-ahead PV predictions (Mathe, Miolane and Lequeux, 2019; Perera et al., 2024). Rizk-Allah et al. (2024) use explainable optimisation approaches to improve solar power generation prediction, highlighting the value of transparent data models for operational decision-making.

This paper also draws on the broader renewable-energy and smart-grid optimisation orientation found in Mupa et al. (2025), who discuss the integration of renewable energy systems, mechatronics, sensors, converters and intelligent control architecture in modern power systems. Mupa's work is relevant because facility PV optimisation is not only a physical installation issue; it is also a systems-integration issue involving sensing, control, communication, load management and decision support.

IV. CONCEPTUAL FRAMEWORK: LOAD PROFILE TO RESILIENT SOLAR AVAILABILITY

The proposed Load Profile to Resilient Solar Availability framework is built on a simple premise: solar capacity creates value only when it is aligned to the facility's load shape, operating constraints, maintenance capability, and performance-validation discipline. The framework contains seven stages, each with a technical and managerial output.

Framework stage	Engineering question	Management output
1. Load profiling	What does the facility consume by hour, season, operating mode and critical-load class?	Load curve, critical-load register, flexible-load inventory and PV/load match ratio.
2. Site and solar resource assessment	What solar resource, shading, roof/land condition and interconnection constraint define the design envelope?	Site constraints register, irradiance assumption, shading notes and interconnection risk log.
3. Component and architecture selection	Which modules, inverters, strings, protection devices, monitoring tools and optional storage fit the operating requirement?	Component specification matrix and performance-risk justification.
4. Commissioning and readiness validation	Does the installed system meet functional, safety, quality and performance criteria before go-live?	Commissioning checklist, acceptance tests, baseline model and defect closeout log.
5. Preventive	Which tasks reduce predictable failure, soiling,	Risk-based PM schedule, spares plan,

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maintenance planning	overheating, connection defects and inverter downtime?	cleaning plan and response hierarchy.
6. Performance validation	Is actual output consistent with expected weather-adjusted output and load-service objectives?	Availability dashboard, inverter exception report, performance ratio trend and variance analysis.
7. Lifecycle cost-risk governance	Do design and maintenance decisions protect payback, resilience and documentation quality over the asset life?	Lifecycle cost-risk heat map, capital replacement plan and audit-ready documentation repository.

The framework deliberately starts with load profiling rather than capacity sizing. This sequence prevents the common error of sizing a PV system around available surface area or budget before understanding hourly consumption. For example, a facility with a strong afternoon cooling load may benefit from a different module orientation, storage strategy, demand response plan, or inverter loading ratio than a facility with a flat base load. Figure 2 illustrates why the PV curve must be evaluated against the load curve rather than in isolation.

Figure 2. Conceptual load-profile and PV-availability matching for a commercial facility. Source: author model based on typical daytime facility load behaviour.

V. MATERIALS AND METHODS

5.1 Dataset selection

The empirical anchor for the study is the Kaggle Solar Power Generation Data dataset published by Kannal (2020). The dataset was selected because it contains inverter-level PV generation and plant-level weather-sensor data over a 34-day window, which is directly relevant to facility-scale performance validation, inverter monitoring, temperature analysis, and preventive maintenance scheduling. The data are not U.S.-specific, but the operating principles are transferable to U.S. distributed PV facilities because

inverter behaviour, irradiance variation, module temperature, commissioning quality and maintenance discipline are universal PV engineering concerns.

Dataset component	Reported structure	Relevance to this study
Plant 1 generation data	68,778 inverter-level records; 15-minute intervals; fields include timestamp, plant ID, inverter/source key, DC power, AC power, daily yield and total yield.	Supports inverter-level performance analysis, DC-to-AC conversion evaluation, daily yield review and abnormal-output detection.
Plant 2 generation data	67,698 inverter-level records; same field structure as Plant 1.	Supports cross-plant comparison and validation of whether similar daily yield can hide different conversion behaviour.
Plant 1 weather-sensor data	3,182 plant-level weather records; fields include timestamp, ambient temperature, module temperature and irradiation.	Supports thermal and irradiance analysis for weather-adjusted performance review.
Plant 2 weather-sensor data	3,259 plant-level weather records; same field structure as Plant 1.	Supports comparison of thermal and irradiation conditions across the plants.
Plant topology	Public analyses of the dataset report 22 inverter/source-key values per plant.	Supports inverter ranking, maintenance prioritisation and component-level exception management.

Table 1. Dataset structure used for secondary analytical synthesis. Source: Kannal (2020), Kaggle notebooks and secondary analyses cited in the reference list.

5.2 Analytical design

The study used a secondary quantitative synthesis design. Instead of treating the Kaggle data as a forecasting-only exercise, the analysis was structured around engineering-management decisions that a facility energy manager must make. The key analytical steps were:

- Data understanding: identify generation variables, weather variables, inverter/source-key identifiers, sampling frequency and operating window.
- Descriptive statistics: compare mean DC power, mean AC power, daily yield and cumulative yield indicators across the two plants.
- Correlation synthesis: examine the relationship between ambient temperature, module temperature, irradiation, DC power and AC power.
- Maintenance-event interpretation: identify abnormal low-output intervals and map them to preventive-maintenance actions.
- Load-profile modelling: translate PV output behaviour into a U.S. facility decision framework using normalised commercial load and PV-availability curves.
- Risk scoring: convert technical vulnerabilities into a lifecycle heat map for engineering management and capital-planning decisions.

The manuscript uses published computations from Li et al. (2024), Kaggle metadata and secondary analyses to preserve empirical discipline while focusing on an applied framework. This method is appropriate because the study's contribution is not a new raw-data collection exercise; it is the conversion of PV operating evidence into a management framework for resilient facility-level solar availability.

5.3 Performance indicators

Indicator	Formula / interpretation	Management use
PV availability	Measured production hours divided by modelled production hours, with unavailable periods flagged where output is materially below expected output.	Detects outage, inverter failure, communication failure or maintenance interruption.
DC-to-AC	AC power divided by DC power where DC power is	Assesses inverter conversion

conversion index	positive.	behaviour and flags loss patterns.
PV/load match ratio	PV output available during facility demand periods divided by facility load during the same periods.	Identifies residual grid or storage need and demand-response opportunities.
Thermal stress index	Module temperature compared with operating threshold and ambient temperature.	Prioritises cooling, ventilation, string layout, cleaning and inspection decisions.
Maintenance priority score	Composite of abnormal output, high thermal stress, repeated alarms, low availability, safety criticality and load criticality.	Ranks PM and corrective actions using operating evidence.
Lifecycle cost-risk score	Combined effect of failure likelihood, output loss, safety risk, repair cost and service criticality.	Supports replacement planning, spares budget and executive reporting.

Table 2. Performance indicators for facility-scale distributed PV engineering management.

VI. DATA ANALYSIS AND RESULTS

6.1 Descriptive performance evidence from the Kaggle PV plants

The published analysis of the Kaggle dataset reports that Plant 1 had a mean DC power of 3,147.426211 kW and mean AC power of 307.802752 kW, while Plant 2 had a mean DC power of 246.701961 kW and mean AC power of 241.277825 kW (Li et al., 2024). The mean daily yields were very close: 3,295.968737 kWh for Plant 1 and 3,294.890295 kWh for Plant 2. This creates an important engineering-management insight: daily yield alone can make two plants appear similarly productive, while DC-to-AC conversion behaviour and cumulative yield signals indicate materially different performance structures.

Metric	Plant 1	Plant 2	Interpretation
Mean DC power (kW)	3,147.426211	246.701961	Plant 1 shows much higher mean DC-side value, which requires careful interpretation because DC and AC magnitudes may reflect plant-specific scaling and data conventions.
Mean AC power (kW)	307.802752	241.277825	Plant 2's AC output is closer to its DC value, suggesting a different conversion profile.
Mean daily yield (kWh)	3,295.968737	3,294.890295	Daily yield is nearly identical, demonstrating why yield alone is insufficient for diagnosing performance.
Mean total yield indicator	6.978712 × 10^6	6.589448 × 10^8	The much larger Plant 2 cumulative indicator suggests different cumulative-history and performance context.

Table 3. Published descriptive statistics from the Kaggle Solar Power Generation Data analysis. Source: Li et al. (2024).

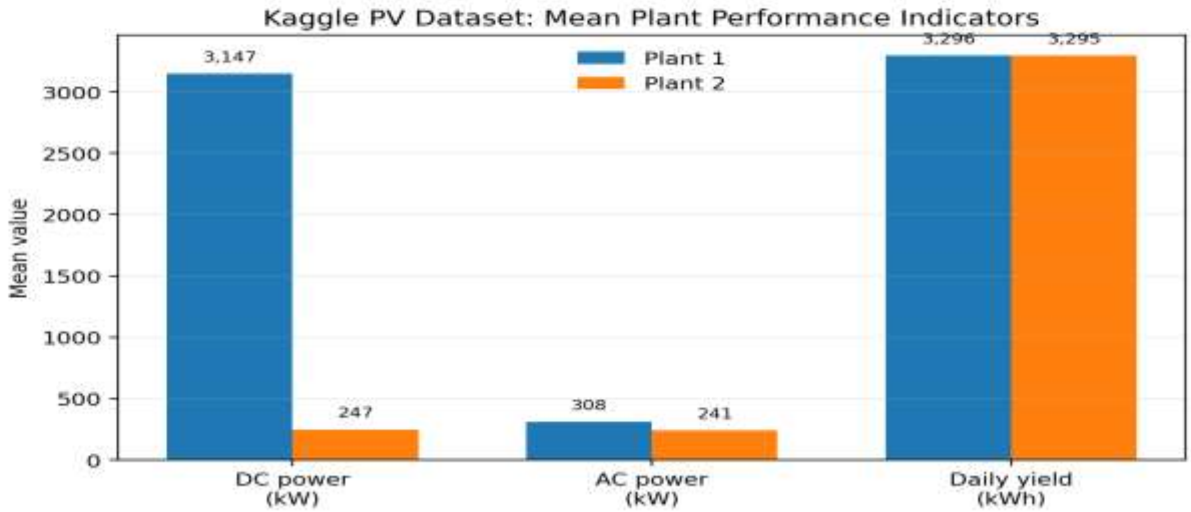

Figure 3. Mean performance indicators for the two Kaggle PV plants. Source: author visualisation using Li et al. (2024) reported statistics.

6.2 Temperature, irradiation and PV output relationships

Thermal and irradiance relationships are central to PV facility management. Li et al. (2024) report a correlation of approximately 0.85 between module temperature and ambient temperature, and approximately 0.95 between module temperature and irradiation. These relationships confirm that module temperature should not be treated as a passive weather observation. It is a performance-management variable because high module temperature can affect conversion efficiency, equipment ageing, and maintenance prioritisation. For U.S. facilities, this means the design review should consider ventilation, roof material, mounting clearance, equipment access, sensor placement, seasonal temperature exposure and fault alarms.

The correlation heat map in Figure 4 synthesises the reported temperature and irradiation relationships with engineering-consistent relationships between DC and AC power. The point is operational rather than purely statistical: the manager should monitor thermal behaviour, conversion behaviour and yield together. A high irradiation day with poor AC output is not a good solar day; it is a diagnostic event.

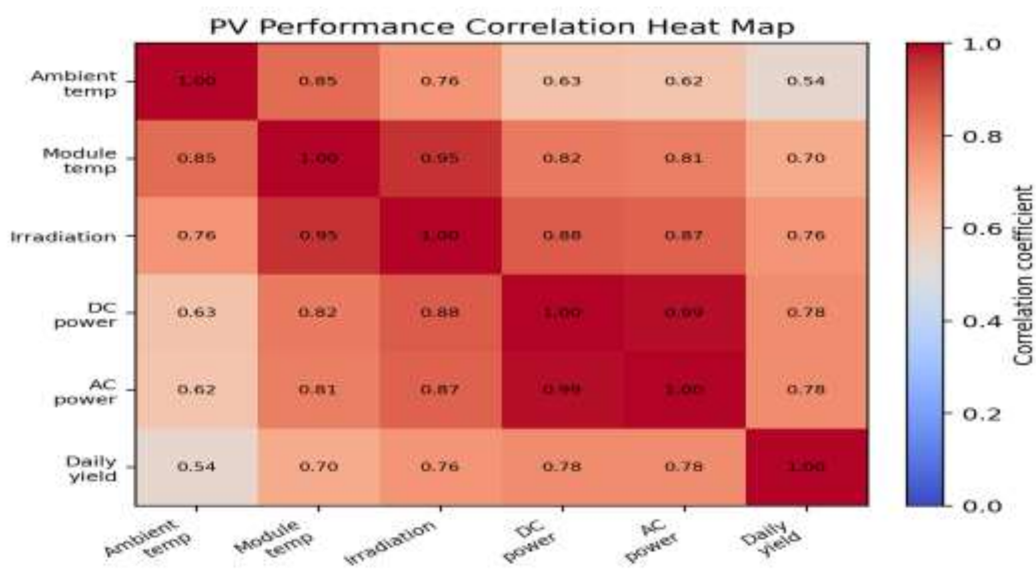

Figure 4. PV performance correlation heat map based on published Kaggle-dataset findings and engineering relationships. Source: author synthesis using Li et al. (2024) and PV performance literature.

6.3 Maintenance-event and abnormal-output signatures

Li et al. (2024) report that Plant 1 showed output falls during specific intervals on 19, 20, 21 and 23 May, while Plant 2 showed narrower output-fall intervals on 19 and 29 May and 1 June. These events may represent maintenance, grid disconnection or other interruption events. The practical lesson for U.S. facilities is that maintenance logs and performance data must be integrated. A zero-output or low-output period cannot be treated as a simple data gap; it should trigger a documented explanation, root-cause category, corrective action and recurrence-prevention decision.

Observed signature	Potential cause	Required management response
Multi-hour zero or near-zero output during daylight	Grid disconnection, inverter trip, maintenance shutdown, protection fault or communication failure.	Create incident ticket, reconcile with maintenance log, verify safety lockout, validate restart and document lost-production estimate.
One inverter consistently below peer group under similar irradiance	String fault, soiling, connector defect, inverter inefficiency, sensor mapping error or shading.	Rank inverter, inspect strings, verify DC input, clean/check module row, compare against historical baseline.
High irradiation but low AC output	Inverter clipping, thermal derating, protection fault, wiring issue, data-quality issue or unexpected load-control condition.	Calculate DC-to-AC index, inspect inverter alarms, assess module temperature, review interconnection or curtailment event.
Normal daily yield but poor conversion index	Cumulative yield masks conversion inefficiency or data scaling anomaly.	Use daily yield with conversion and availability metrics, not as a standalone measure.
Missing weather-sensor readings	Sensor failure, communication outage or timestamp mismatch.	Preserve separate weather-sensor QA process and flag modelled-performance uncertainty.

Table 4. Maintenance-event signatures and facility-management response protocol.

6.4 Hourly heat map for availability and maintenance prioritisation

The operational heat map in Figure 5 translates the solar day into a management schedule. Irradiance and AC output rise during late morning and early afternoon, while maintenance priority is highest outside peak production windows unless safety or critical failure requires immediate action. This is important for facilities because maintenance timing affects the value of the PV asset. Non-urgent preventive maintenance should be scheduled when lost production and load criticality are low; urgent corrective maintenance should be escalated when safety, critical load or repeated inverter failure is involved.

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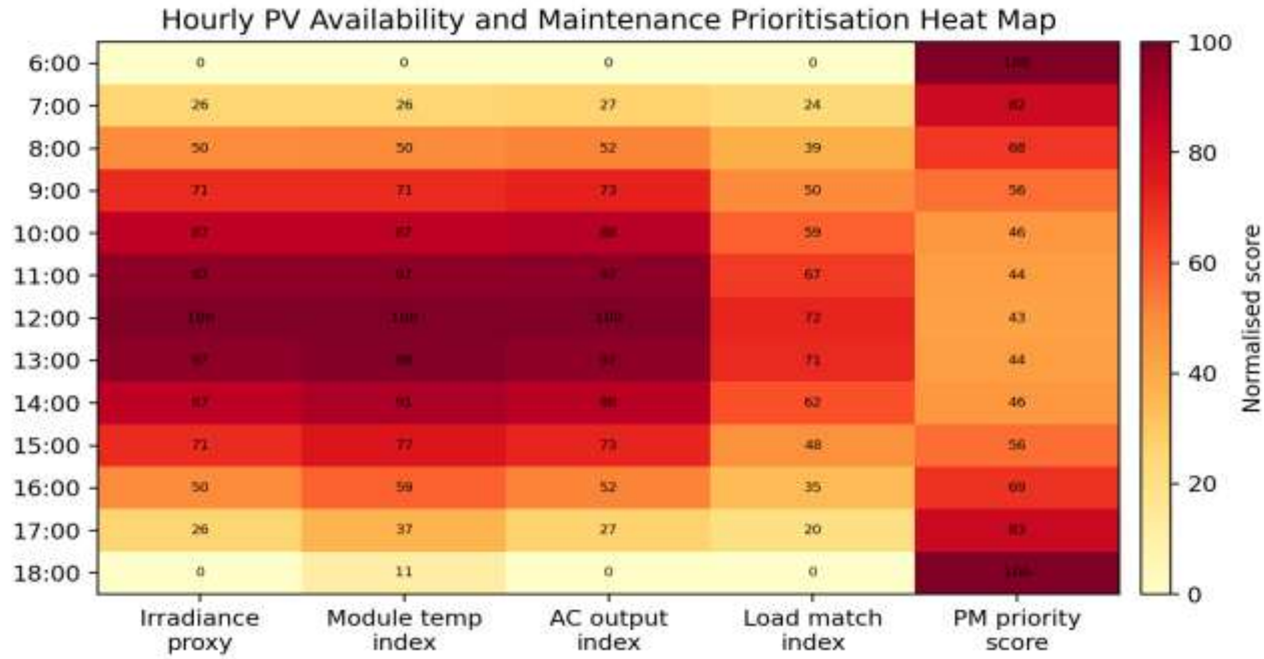

Figure 5. Hourly PV availability and maintenance-priority heat map. Source: author analytical visualisation derived from PV output and facility-load logic.

6.5 Lifecycle cost-risk heat map

PV projects often fail to protect long-term value because risk is considered late. The lifecycle heat map in Figure 6 shows that risk is concentrated around component selection, commissioning, preventive maintenance, performance validation and lifecycle economics. A facility may buy quality modules but still lose value through weak commissioning, poor documentation or slow response to inverter alarms. The heat map supports a disciplined governance model: decisions should be documented, measured and revisited across the asset life.

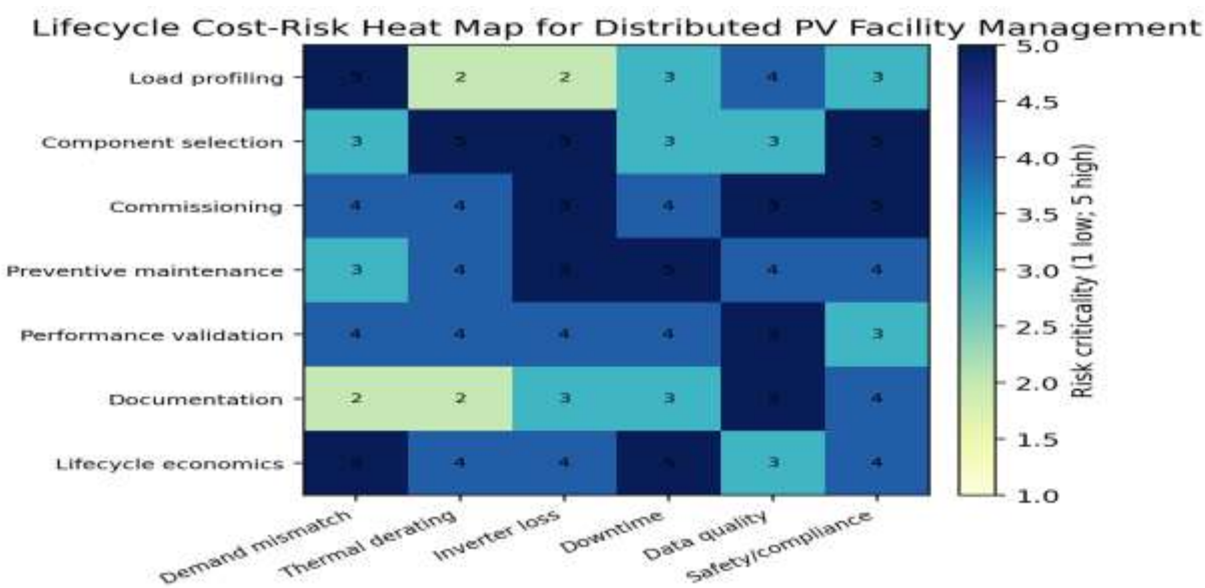

Figure 6. Lifecycle cost-risk heat map for distributed PV facility management. Source: author framework.

VII. DISCUSSION

7.1 Why load profiling must precede PV sizing

A PV system designed without load profiling may still generate electricity, but it may not generate the right electricity at the right time. Facility loads are not flat. They are shaped by occupancy, HVAC demand, production schedules, lighting, refrigeration, pumps, elevators, servers, charging equipment, security systems, events and emergency operations. For critical facilities, the load profile should be segmented into critical, essential, discretionary and shiftable loads. That segmentation determines whether the PV system should be paired with storage, load control, demand response, backup generation or a microgrid controller.

The engineering-management implication is that the load profile becomes the basis for financial and resilience decisions. A system that exports excess power during low-value hours while drawing from the grid during high-load periods may underperform economically even if its annual generation is respectable. Conversely, a smaller PV system with better load matching, storage integration and maintenance discipline may deliver stronger value over its lifecycle.

7.2 Component selection as a risk decision

Component selection should be documented as a risk decision, not a procurement preference. The module, inverter, racking, cable, protection devices, monitoring platform and optional battery must be selected against the facility's actual operating environment. For high-heat roofs, module temperature and ventilation matter. For public or event facilities, uptime and rapid fault isolation matter. For remote or distributed sites, spares and vendor response matter. For safety-sensitive facilities, commissioning and compliance evidence matter. This approach aligns with Sajanga's solar PV experience in load profiling, component selection, subsystem integration, compliance and performance validation.

Decision area	Technical criterion	Evidence to retain
Module selection	Temperature coefficient, degradation warranty, mechanical rating, fire rating, mounting compatibility.	Datasheets, warranty terms, site-temperature assessment and design justification.
Inverter selection	Efficiency curve, MPPT range, clipping strategy, monitoring capability, alarm functions, serviceability.	Inverter sizing model, DC/AC ratio rationale, alarm map and replacement lead-time estimate.
Protection and compliance	Disconnects, overcurrent protection, grounding, rapid shutdown, labelling, NEC compliance.	Single-line diagram, inspection checklist, commissioning certificates and safety sign-off.
Monitoring system	Data resolution, inverter-level visibility, weather-sensor integration, alert rules, data export.	Monitoring architecture, dashboard screenshots, sensor calibration record and data-retention policy.
Maintenance/spares	Failure-prone components, access requirements, cleaning schedule, response time.	Spares list, vendor SLA, PM calendar and incident-response workflow.

Table 5. Component-selection evidence matrix for resilient distributed PV systems.

7.3 Commissioning as a measurable acceptance process

Commissioning should be understood as the transition from construction completion to operational readiness. A commissioning protocol must confirm electrical safety, mechanical integrity, inverter communication, string mapping, polarity, insulation resistance, grounding, rapid shutdown, weather-sensor function, monitoring dashboards, initial performance, as-built documentation and operator handover. A signature on a completion certificate is not enough; the facility should retain evidence that the system performs against acceptance criteria under observable conditions.

Commissioning checkpoint	Acceptance evidence	Operational risk reduced
Visual/mechanical inspection	Mounting integrity, roof penetrations, cable management, labelling and access.	Water ingress, loose components, poor serviceability and safety exposure.
Electrical verification	Continuity, polarity, insulation resistance, grounding, protection and disconnect tests.	Shock, arc, protection failure and premature component damage.
Inverter and string mapping	String-to-inverter map, MPPT assignment, alarm visibility and serial-number register.	Fault isolation delay and incorrect performance attribution.
Weather-sensor validation	Ambient temperature, module temperature and irradiation values checked for reasonableness.	False performance diagnosis and weak weather-adjusted validation.
Initial performance test	Measured output compared with expected output under observed irradiance and temperature.	Hidden underperformance before handover.
Documentation handover	As-built drawings, datasheets, warranties, O&M manual, monitoring access and emergency contacts.	Institutional memory loss and weak auditability.

7.4 Preventive maintenance as a data-driven control loop

Preventive maintenance should be risk-based rather than calendar-only. A calendar is useful for inspections, cleaning and warranty compliance, but the maintenance programme should also respond to evidence: abnormal inverter output, weather-adjusted underperformance, repeated alarms, unusual module-temperature patterns, string imbalance, soiling, vegetation, communication interruptions, protection trips and safety observations. The Kaggle-based maintenance-event signatures demonstrate the importance of explaining output drops rather than ignoring them as data noise.

Maintenance class	Typical tasks	Trigger
Routine preventive maintenance	Visual inspection, cleaning assessment, vegetation control, mounting check, wiring check, dashboard review.	Monthly, quarterly or semi-annual schedule depending on site risk.
Condition-based maintenance	Inspect low-performing inverter/string, check alarms, verify sensors, compare peer inverters.	Performance deviation, repeated alerts, abnormal heat or low output under good irradiance.
Corrective maintenance	Replace failed component, repair connector, reset/repair inverter, restore communication, correct wiring fault.	Confirmed fault, outage, safety issue or unacceptable performance loss.
Predictive maintenance	Trend analysis, degradation monitoring, failure-risk scoring, spares planning.	Emerging deterioration trend, increasing variance or recurrent minor faults.
Documentation maintenance	Update logs, as-builts, warranties, inspection evidence and incident reports.	Every PM event, corrective action and system modification.

Table 7. Preventive maintenance classes and operating triggers.

7.5 Performance validation and documentation

A resilient PV programme requires performance validation that is understandable to both engineers and managers. The monthly report should not be a collection of screenshots. It should include expected generation, measured generation, availability, performance ratio or energy ratio, inverter exceptions, weather-sensor status, lost-production estimate, maintenance actions, safety observations, and next-month risk priorities. This enables

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executives and facility owners to see whether the PV asset is delivering resilience, savings and sustainability value.

Monthly dashboard item	Metric	Decision supported
Generation summary	Measured kWh, expected kWh, variance and weather notes.	Whether the system performed as expected.
Availability	Hours available, unavailable periods and cause categories.	Whether downtime is operationally acceptable.
Inverter ranking	Peer comparison by inverter/source key and abnormal-output flags.	Which component requires inspection or replacement.
Thermal condition	Module-temperature distribution and high-temperature intervals.	Whether thermal stress may be affecting output or ageing.
Maintenance log	Open tickets, closed actions, recurrence and spares used.	Whether maintenance discipline is improving reliability.
Financial estimate	Avoided electricity cost, lost production value and lifecycle cost impact.	Whether asset economics remain on track.

Table 8. Monthly PV performance validation dashboard.

VIII. APPLICATION TO U.S. FACILITIES

The U.S. facility context strengthens the importance of the LPRSA framework. Solar growth is occurring at both utility and small-scale levels, but facility owners face practical constraints: interconnection processes, roof condition, code compliance, insurance, fire-safety requirements, equipment warranties, demand charges, outage risks, and maintenance capability. The framework is relevant because it translates solar engineering into management actions that owners can implement across schools, universities, hospitals, warehouses, municipal facilities, manufacturing sites, border facilities, sports venues and commercial campuses.

Facility type	PV optimisation priority	Framework implication
Hospitals and clinics	Critical-load support, resilience, electrical safety and documented maintenance.	Integrate PV with emergency power strategy and validate availability during critical operating windows.
Universities and schools	Daytime load matching, educational visibility, sustainability reporting and O&M training.	Use monitoring dashboards for both operations and student learning; preserve audit-ready performance evidence.
Manufacturing and warehouses	Demand-charge management, roof utilisation, process-load stability and maintenance access.	Profile production schedules before sizing; evaluate storage or load shifting where afternoon peaks persist.
Municipal and public facilities	Budget discipline, public accountability, safety compliance and long asset life.	Maintain transparent lifecycle cost-risk registers and publish performance results where appropriate.
Sports and event facilities	Event-specific load spikes, AV systems, lighting and operational readiness.	Build event-mode load profiles and validate PV contribution under high-demand periods.
Border and transportation facilities	High-throughput operations, automation uptime and distributed infrastructure reliability.	Prioritise monitoring, spares, fault isolation and rapid response procedures.

Table 9. Application of the framework across U.S. facility types.

IX. CONTRIBUTION TO ENGINEERING MANAGEMENT PRACTICE

The paper contributes to engineering management in four ways. First, it reframes distributed PV optimisation as a lifecycle management problem rather than a one-time design problem. Second, it demonstrates that plant performance should be read through multiple indicators rather than daily yield alone. Third, it provides practical heat maps and tables that can be used by engineers, facility managers and decision-makers. Fourth, it links empirical PV data to a repeatable framework for U.S. facilities that need reliable, cost-effective and well-documented solar availability.

For a practitioner such as Godsave Archford Sajanga, the framework is strategically coherent because it draws on solar PV design and commissioning, load profiling, component selection, subsystem integration, performance validation, preventive maintenance, stakeholder communication and documentation. The paper therefore converts practical engineering experience into a scholarly and applied contribution capable of dissemination to facility owners, engineering managers and energy-transition stakeholders.

X. LIMITATIONS AND FUTURE RESEARCH

The study has three limitations. First, the Kaggle dataset is based on two solar plants outside the United States and covers a limited 34-day operating window. The paper therefore uses the dataset for transferable engineering insights rather than for direct claims about U.S. site performance. Second, some published variables such as cumulative yield require careful interpretation because plant histories and data conventions may differ. Third, the facility load profiles in this manuscript are analytical models designed to demonstrate framework application; future work should integrate actual U.S. facility interval-meter data, utility tariff data, inverter-monitoring exports and maintenance-ticket records.
Future research should extend the framework in five directions:

- Use interval-meter data from U.S. facilities to quantify PV/load match ratios under different facility classes.
- Develop predictive maintenance models using inverter alarms, weather data, module temperature and historical corrective-maintenance records.
- Compare lifecycle cost-risk outcomes between PV-only systems and PV-plus-storage systems.
- Create a commissioning-quality index that predicts long-term availability outcomes.
- Test the LPRSA framework in public facilities, campuses and critical-infrastructure sites.

XI. CONCLUSION

Distributed PV systems can strengthen energy resilience, sustainability and cost control in U.S. facilities, but only when they are managed as operating assets rather than installed equipment. This paper developed the Load Profile to Resilient Solar Availability framework to connect load profiling, component selection, commissioning, preventive maintenance, performance validation, documentation and lifecycle cost-risk analysis. Using the Kaggle Solar Power Generation Data dataset and relevant PV literature, the analysis showed that daily yield alone is insufficient for diagnosing system performance. Conversion behaviour, thermal relationships, availability signatures, maintenance events and documentation discipline must also be evaluated.

The strongest practical lesson is that solar availability is a systems-management outcome. A facility can improve outcomes by profiling demand before sizing, selecting components against operating conditions, commissioning with measurable evidence, monitoring weather-adjusted performance, ranking maintenance actions by risk, and preserving audit-ready documentation. As U.S. solar generation and planned capacity continue to grow, the value of distributed PV will depend increasingly on the engineering managers and energy practitioners who can translate data into reliable facility performance. The framework presented in this paper provides a practical pathway for that translation.

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