



Benchmarking of solar farms: A SMART framework for energy auditing and performance evaluation

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ABSTRACT

Energy auditing is critical for sustaining the performance and reliability of solar power plants, yet current practices are fragmented and lack a standardised approach for industry application. This study introduces the SMART (specific, measurable, achievable, relevant, and time-bound) framework, a first-of-its-kind, standards-aligned methodology that unifies verified performance equations, benchmark thresholds, and mitigation strategies drawn from internationally recognised standards and peer-reviewed literature. Unlike conventional audits that assess isolated metrics, the SMART framework integrates data acquisition, performance evaluation, loss analysis, and corrective planning into one reproducible process. It benchmarks key performance indicators, including system efficiency, specific yield, performance ratio (PR), and temperature and mismatch losses, to provide clear, actionable insights into plant operation. Designed for direct industry use, the framework is practical, scalable, and adaptable across diverse plant sizes and configurations. By transforming scattered academic knowledge into a structured, field-ready toolkit, this study establishes a groundbreaking pathway for transparent and replicable solar power plant auditing.

1 Introduction

Solar power plants have become a crucial part of the global renewable energy landscape, helping to combat climate change and reduce reliance on fossil fuels [1]. Over the past few years, significant

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technological advancements have propelled the solar industry forward [2]. Despite rapid improvements in module efficiency, inverter technology, and plant scale, many utility-scale solar farms continue to underperform relative to their design potential. Performance degradation caused by thermal stress, soiling, mismatch losses, and suboptimal inverter operation remains a persistent challenge. Maintaining optimal operational efficiency in utility-scale photovoltaic (PV) installations remains an ongoing challenge despite significant technological advancements in the sector [3,4].

Energy auditing provides a structured means of comparing actual energy generation against expected output, enabling the identification of avoidable losses and operational inefficiencies. However, current solar auditing practices are often fragmented, site-specific, and difficult to replicate across plants of different sizes and configurations. While international standards define key performance indicators, they do not offer an integrated operational framework suitable for routine field application [4]. In summary, energy auditing is essential for maximising solar power plant performance, ensuring long-term sustainability, and supporting the transition to a low-carbon energy future [5]. This study consolidates verified performance equations, benchmarks, and mitigation strategies from international standards and peer-reviewed literature into a unified SMART (specific, measurable, achievable, relevant, and time-bound) framework. Designed for direct industry application, this framework enables plant operators, regulators, and consultants to independently audit the performance of any utility-scale solar farm.

Studies on solar energy performance commonly apply standard metrics to evaluate system efficiency and operational consistency under different climatic and geographic conditions. Among these indicators, the performance ratio (PR) is widely used for comparison between systems exposed to varying environmental stresses. From 2020 to 2025, research has increasingly centred on the PR as a practical tool for identifying losses and improving system operation. Owolabi et al. [6] compared PV technologies in Nigeria and found that high temperatures strongly influence PV system suitability. Likewise, Palm et al. [7] examined solar generation in Burkina Faso and reported similar thermal-related output reductions. These findings emphasise the role of thermal conditions in performance evaluation. Other studies address land use and social needs. Beyond utility-scale plants, energy auditing studies extend to buildings and infrastructure. Chisale and Mangani [8] evaluated a commercial building in Malawi and demonstrated the feasibility of solar PV integration for energy savings. Bosu et al. [9] conducted an energy audit in a residential building in Egypt and found that PV systems achieved greater energy and carbon reductions than solar water heating. Kumar et al. [10] observed higher degradation rates in a canal-top solar plant in India compared to ground-mounted systems, despite acceptable PRs. Research by Tajjour et al. [11,12] showed that optimised panel orientation in hilly regions reduces energy losses and improves output. For long-range planning, Islam et al. [13] analysed degradation trends in tropical countries to estimate future power decline and support financial viability assessments. Beyond technical assessment, performance indicators are widely applied in energy auditing. Institutional audits at Brahmananda Keshab Chandra College (BKCC) [14] and East Point College (EPC) [15] demonstrated cost reductions through solar integration and efficient energy management. These studies show that standard metrics are adapted to address local environmental, spatial, and operational challenges.

International standards like IEC 61724-2 and IEC 61853 offer reliable procedures for monitoring PV systems. However, they mainly specify measurement and calculation methods. They do not provide a complete auditing workflow. Consequently, practitioners are left to combine multiple standards, empirical relations, and maintenance protocols during field inspections. This practice varies widely across installations. It introduces inconsistency into routine performance assessments and operation and maintenance (O&M) protocols. This fragmented approach to solar plant performance creates a clear gap. The proposed SMART framework directly addresses this gap. It consolidates internationally accepted standards, validated performance metrics, degradation evaluation, benchmark references, and remedial measures. These components are integrated into a single reproducible methodology suitable for real-world field application. This study presents a SMART framework, structured and application-oriented for energy auditing in utility-scale solar farms. This novel and comprehensive framework integrates data acquisition, performance benchmarking, loss analysis, and corrective planning into a single reproducible audit process. The framework is designed for direct use by plant operators, consultants, and regulators, providing a practical pathway for transparent, scalable, and repeatable performance evaluation of utility-scale solar farms.

The study is organised into five sections. Section 1 deals with a brief background of the topic. Section 2 introduces the main components of utility-scale solar farms. Section 3 presents the development of the SMART framework, including the auditing methodology, technical indicators, and benchmarking procedures. Section 4 demonstrates the application of the framework and discusses performance evaluation, degradation assessment, and optimisation strategies. Finally, Section 5 summarises the main findings and future applicability of the framework.

2 Basic description of solar farm

Large-scale grid-connected solar farms comprise PV modules, inverters, DC/AC cabling, weather monitoring systems, optional battery storage, and mounting infrastructure (Fig. S1 in Appendix A). While offering scalable renewable generation, utility-scale installations face operational trade-offs, such as land allocation and PV arrays optimised for site-specific tilt and azimuth angles to maximise solar irradiance capture [16]. The advantages and disadvantages of the solar farm are illustrated in Fig. S2 in Appendix A. Despite some minor drawbacks, large-scale solar farms are critical for meeting substantial electricity demands at the national level [17]. Understanding the functions and interactions of these solar farm components provides the foundation for developing the SMART framework. The following methodology describes how these components are systematically evaluated through a structured energy auditing process.

3 Methodology of the SMART framework

The SMART framework in Fig. 1 adopts a structured three-phase methodology to evaluate and enhance solar farm performance. The first phase establishes a baseline through site data collection, review of historical utility records, and preliminary visual inspection. This phase identifies immediate anomalies and defines audit priorities. This is done through the examination of utility data, on-site visual inspection, and an analysis of original design specifications. The second phase involves detailed technical auditing of PV modules, inverters, and grid interfaces. These components are analysed and critically examined using verified international standards to determine their current energy output and conversion efficiency. Component-level assessment ensures accurate diagnosis of performance deviations. The final phase involves performance benchmarking against established industrial standards. Underperforming systems are provided with targeted improvement recommendations, enabling iterative performance enhancement. This integrated structure distinguishes the SMART framework from conventional audits by linking diagnostics directly to corrective action.

3.1 Phase 1: Preliminary energy auditing procedure

The preliminary audit provides an initial assessment of solar farm performance through site inspection and basic data review. This would be helpful to understand how the solar farm operates. It begins with verification of key plant details and analysis of historical utility records to establish baseline generation and identify abnormal trends. All supporting data, including the site assessment data sheet, inspection checklists, design compliance verifications, solar farm equipment baseline records, and weather/operational trend analyses, are compiled in Tables S1–S5 in Appendix A, respectively. A standard template keeps this data organised. During the physical inspection, auditors examine the condition of PV modules, inverters, electrical connections, and mounting structures. Visible issues such as cracked panels, loose wires, rust, or dirt are recorded, as these factors directly influence energy output [18]. Shading sources, including nearby vegetation, are carefully noted [4]. A concise inspection checklist and preliminary utility data review are provided. Finally, energy auditors compare design specifications with actual field conditions. Panel tilt, wiring, and safety systems are matched with the plans and optimised according to the site. Compliance of cabling, earthing, and junction boxes with design and safety requirements is also confirmed. Local weather data, including solar irradiance, ambient temperature, humidity, wind speed, and rainfall, are incorporated to interpret system behaviour. Historical operational and climatic records are examined to identify recurring performance issues. This combined review highlights performance gaps and guides the need for further detailed auditing.

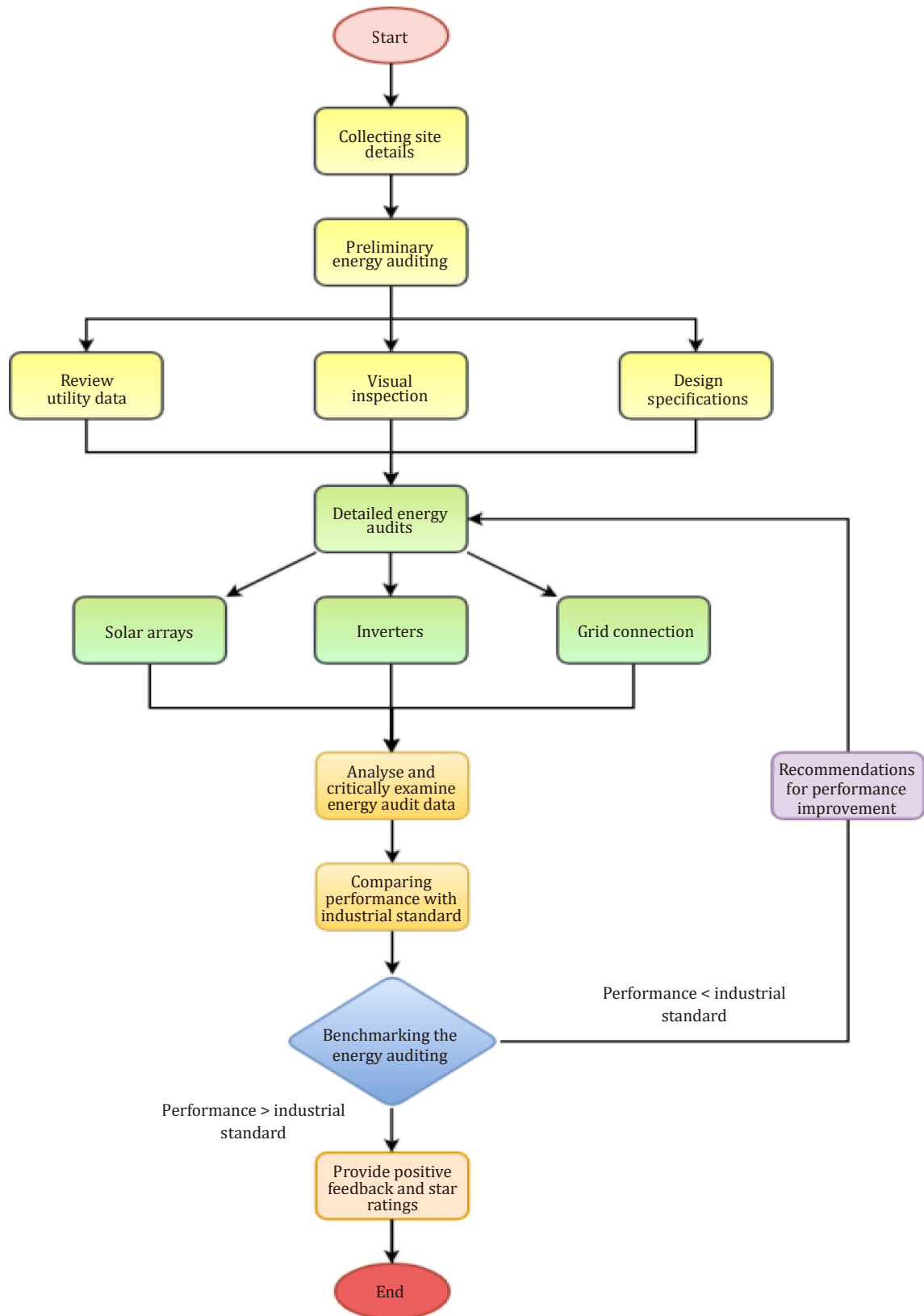


Fig. 1. Step-by-step procedure for solar farm energy auditing and benchmarking.

3.2 Phase 2: Detailed energy auditing procedure

A detailed energy audit of a solar farm is a rigorous, data-driven evaluation of a solar PV system's performance, focusing on energy generation, consumption, and efficiency across critical components such as PV modules and inverters. Fig. 2 shows the graphical illustration of the technical audit which should be performed. Unlike preliminary audits, detailed energy audits quantify energy flows and loss mechanisms, enabling comprehensive identification of performance. This process enables the identification of performance deviations, system inefficiencies, and optimisation opportunities for optimising plant operation and maximising long-term efficiency and reliability.

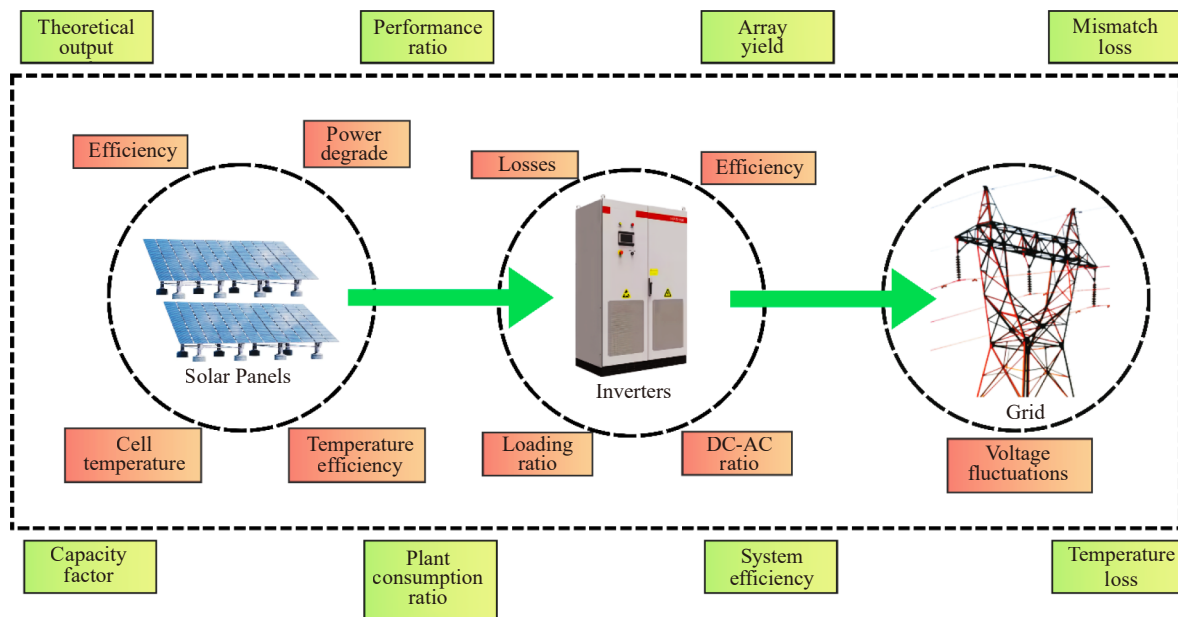


Fig. 2. Key parameters for technical audit of solar power plants.

3.3 Technical and climate parameters

All technical indicators and performance formulas embedded in the SMART framework are adopted from internationally recognised sources, including IEC 61724-2 (PR and data quality requirements), IEC 61853 (module energy rating), and IEA PVPS Task 13 best-practice guidelines. Each key performance indicators (KPI) definition and threshold range has been cross-verified with peer-reviewed empirical studies and industrial performance reports. This approach ensures methodological rigour and assures that the framework is scientifically grounded and directly applicable in real-world solar power plant audits.

The relevance of these standards to each stage of the SMART framework is stated clearly below. Methodological alignment with recognised guidelines is central to the framework's validity and its practical use in the field. IEC 61724-2 establishes the foundation for operational monitoring. It defines collection procedures for environmental and electrical measurements, including irradiance, temperature, voltage, and current. These procedures ensure consistency and reliability in PR calculations, energy yield assessments, and data quality checks. The Framework applies these requirements during the initial data acquisition and technical auditing phases.

IEC 61853 provides complementary standardised methods for evaluating PV module energy ratings. These methods account for varying irradiance and temperature conditions. The framework draws on this standard for module efficiency calculations, temperature coefficient assessments, and theoretical energy output estimates. This allows direct comparison between measured field performance and expected module behaviour. The benchmarking and performance interpretation stages adopt recommendations from IEA PVPS Task 13. This source offers internationally accepted guidance for diagnosing operational losses, including mismatch, temperature, inverter, and degradation losses.

The SMART framework does not introduce new performance equations. Instead, it integrates these existing standards into a single operational workflow. It transforms independent technical guidelines into a unified energy auditing methodology suited for field implementation. The Framework adopts the threshold values presented in Table 1 from these sources. When an auditor compares measured plant indicators against the benchmark table, they are effectively comparing the plant against the same reference base used across international PV monitoring literature. Linking the data collection protocol, KPI formulas, and benchmark thresholds allows the SMART framework to be described as aligned standards. Each output the framework produces can be traced back to a specific clause or guideline. Auditors, plant operators, and regulators therefore receive a verifiable basis for every number the audit generates.

Table 1

Benchmark values and mitigation strategies for each parameter.

Parameter	Benchmark	Mitigation strategies
PV efficiency	18%–22%	• Minimize shading and soiling • Install cooling system for PV • Use advanced PV technology
Power degrade	0.5%–0.8% per year	• Regular maintenance • Use PV with low degradation rate • Ensure proper installation
Cell temperature	45°C–55 °C	• Regular maintenance • Use PV with low temperature coefficient
Temperature coefficient	–0.3%–0.5% per °C	• Install cooling system for PV
Inverter loading ratio (ILR)	1.1–1.2	• Avoid overloading or underloading • Optimise inverter power for PV array • Monitor inverter performance
Inverter efficiency	95%–98%	• Regular maintenance • Install cooling system for inverter
Inverter loss	2%–4%	• Use highly efficient inverter • Regular maintenance • Install cooling system for inverter
Conduction loss	1%–2%	• Use high quality wiring and installation • Minimize cable length • Use appropriate cable sizes
Switching loss	1%–2%	• Use advanced inverter with low switching loss • Optimise switching frequency
Voltage fluctuations	±5 V	• Use voltage regulators • Ensure proper grid synchronization
Theoretical output	Depending on the installed capacity	• Optimise tilt angle and orientation • Use highly efficient PV • Regular maintenance
PR	75%–85%	
AY	1000–2000 kWh per kWp	• Regular maintenance
CF	15%–25%	• Ensure sufficient inverter power
PR degradation rate	≤ 0.8% per year	• Optimise system design • Optimise tilt angle and orientation
PCR	2%–5%	
System efficiency	>23%	• Regular maintenance
Annual degradation rate	0.5%–0.8% per year	• Optimise all components • Minimise losses
Mismatch loss	1%–3%	• Use PV with same electrical characteristics • Avoid shading and soiling
Temperature loss	5%–15%	• Install highly efficient PV cooling system • Use PV with low temperature coefficient

3.3.1 Climate data collection

Precise monitoring of solar irradiance and ambient temperature is vital for assessing PV system performance. Temporal analysis of these parameters captures environmental variability that directly influences module output and energy yield. This data serves as the technical baseline for forecasting

generation potential, sizing storage solutions, and refining grid integration and maintenance protocols. Both figures are compiled in Fig. S3 in Appendix A. Fig. S3(a) in Appendix A presents the plotting template developed in this study for visualising climatic data, whereas Fig. S3(b) in Appendix A demonstrates its application using actual research data to illustrate how the template can be used in practice [19].

3.3.2 Key components: Data collection

Systematic data collection from key components is essential for accurate assessment of PV plant performance and early detection of degradation. Continuous monitoring of PV modules enables timely identification of efficiency reductions and output declines, facilitating maintenance actions that prolong component life and reduce operating costs. Core parameters include module efficiency, power degradation rate, cell operating temperature, and temperature-related efficiency losses, as summarised in Table S6 in Appendix A [20,21]. Common design practice adopts inverter sizing ranging from parity with installed PV capacity to moderate under-sizing at approximately 70%. Accordingly, the conversion stage is audited by evaluating inverter performance through metrics such as the loading ratio and conversion efficiency, as presented in Table S7 in Appendix A [21–25]. Simultaneously, the grid interface must be assessed for voltage stability and power quality to mitigate the effects of variable irradiance. These parameters are evaluated using established analytical expressions, detailed in Table S8 in Appendix A [26].

At the system level, energy yield indicators such as PR, array yield (AY), and theoretical output are calculated to evaluate overall behaviour (Table S9(a) in Appendix A) [13,21,27]. In addition to instantaneous performance indicators, the SMART framework incorporates annual degradation assessment to evaluate the long-term health of the PV plant. Annual degradation rate and annual PR degradation are derived from historical operational records to quantify the progressive decline in energy production over successive years. Unlike short-term performance losses caused by weather or temporary operational issues, annual degradation reflects irreversible ageing of PV modules and balance-of-system components. Incorporating degradation assessment enables auditors to distinguish normal ageing from abnormal deterioration, thereby supporting long-term maintenance planning and asset management.

Additional metrics, including system efficiency, capacity factor, plant consumption ratio (PRC), and annual plant output degradation rate [13], provide a comprehensive view of plant operation, as compiled in Table S9(b) in Appendix A [13,27,28]. Finally, loss data are quantified to isolate mismatch and temperature-related losses, supporting informed corrective actions (Table S9(c) in Appendix A) [28,29]. Comparative evaluations of PV modules, inverters, and storage options are provided in Tables S10–S12 in Appendix A [30–32].

3.4 Instrumentation for a detailed energy auditing

Despite the presence of advanced monitoring systems in solar farms, independent energy audits using high precision, calibrated, well-maintained instruments are crucial for accurate and reliable energy auditing. This ensures minimisation of measurement errors and enables a comprehensive evaluation of plant performance under actual operating conditions. Essential instruments for detailed energy audits are summarised in Table S13 in Appendix A. This comprehensive toolkit enables an energy auditor to perform detailed and high-fidelity assessments of both the PV generation and inverter performance, as well as the interaction of the system with the electrical grid. The proposed SMART framework was applied to demonstrate how preliminary inspection, detailed technical assessment, benchmarking, and degradation evaluation collectively support systematic energy auditing.

4 Results and discussion: Application of the SMART framework

4.1 Preliminary energy auditing findings

The preliminary energy audit offers an initial evaluation of the solar PV farm. Site inspections and utility data analysis revealed issues related to module handling, inverter operation, electrical connections, and equipment condition. Shading and soiling were identified as the major contributors to performance loss, which is due to improper maintenance scheduling. To fix this, the audit recommends regular cleaning and

proper upkeep of electrical components to improve energy output and reduce costs. Its findings are limited by the short assessment period and available monitoring tools [4]. Fig. S4 in Appendix A shows the sample visual inspection audit.

4.2 Detailed energy auditing findings

Detailed energy auditing delivers a comprehensive evaluation of a solar farm's generation, conversion, and efficiency by analysing PV modules, inverters, grid connections, system yields, and losses. Through systematic analysis, a detailed energy audit identifies performance inefficiencies and degradation trends, enabling targeted maintenance and optimisation that improve reliability and energy output.

4.2.1 Analysis of PV module performance

PV module efficiency is a key determinant of solar plant output and declines over time due to degradation, typically expressed as an annual percentage loss. Accurate quantification of this rate enables predictive maintenance and informed scheduling of module replacements. Advanced diagnostic tools such as electroluminescence (EL) imaging have proven effective in identifying microcracks, inactive regions, and early-stage cell failures, particularly in ageing or underperforming modules [20]. Thermal behaviour remains a critical factor in PV performance. Elevated surface temperatures reduce open-circuit voltage (V_{oc}) and slightly increase short-circuit current (I_{sc}), leading to net power losses. The temperature coefficient (β) provides a practical metric for quantifying this sensitivity. Continuous monitoring and innovative cooling strategies, such as radiative, evaporative, or thermoelectric methods, can mitigate thermal losses, enhancing module lifespan and energy yield [33].

4.2.2 Inverter performance and optimization

Inverters convert direct current (DC) from solar panels into alternating current (AC) for grid use. Their performance depends on proper sizing and setup, aiming for a balance that maximises energy without causing overloads. A DC to AC ratio of about 1.1 to 1.2 balances cost and efficiency. Regular audits reduce losses through proper selection, thermal management, and periodic maintenance. Additionally, the ILR indicates operational utilisation, with an ideal ILR near 100% [23].

4.2.3 Grid connection and stability

Stable grid connection is vital for efficient power transmission and system reliability. Fluctuations in solar irradiance can induce voltage instability, which can degrade power quality and affect equipment lifespan. Monitoring and analyzing these fluctuations ensures the PV system operates within acceptable limits, maintaining grid stability and enhancing overall plant performance [26].

4.2.4 Overall plant system performance

Ideal plant output provides a reference for assessing real performance. Key measurements include the PR to identify energy losses. AY and capacity factor (CF) reflect energy production relative to capacity and time [27]. The PCR measures internal energy use. Both the annual degradation rate of the PR and the whole system revealed critical insights into the solar farm performance for each year [34]. Together, these indicators provide a comprehensive evaluation of solar farm efficiency.

4.2.5 Annual degradation assessment

The SMART framework evaluates annual degradation as a key indicator of long-term PV system reliability. Annual degradation rate quantifies the reduction in energy production between successive years, while annual PR degradation evaluates changes in system performance independent of climatic variability. Monitoring these indicators enables plant operators to distinguish normal ageing from abnormal performance deterioration caused by inadequate maintenance, equipment failure, or environmental stress. When degradation exceeds the benchmark value of 0.8% per year, corrective actions such as detailed component inspection, preventive maintenance, or equipment replacement should be initiated. Integrating annual degradation into the SMART framework extends conventional energy auditing beyond short-term performance evaluation toward lifecycle-based asset management.

4.2.6 Energy losses

Energy losses in a solar farm arise from shading, temperature effects, and wiring inconsistencies. Mismatch losses caused by non-uniform electrical characteristics among modules disrupt current flow in series strings, leading to a disruption of current flow and reducing efficiency. These losses can be minimised through targeted strategies such as module binning and optimised string configurations [29]. Thermal losses, driven by elevated module temperatures, further degrade performance. Recent advancements in passive and active cooling techniques have demonstrated improvements in energy yield and operational longevity. Addressing these loss mechanisms is critical for enhancing PRs and ensuring cost-effective long-term operation [33].

4.3 Benchmarking of plant performance

The software interface presented in Appendix A allows operators to input measured and monitored data from their solar farm and obtain computed results for each performance parameter discussed above. A simple colour coding system allows for quick interpretation of these results. A green display indicates that the measured value is within the acceptable range and no further action is required. A yellow display indicates a slight deviation from the benchmark, but this condition does not call for any immediate mitigation measures. However, a red display shows a significant deviation from the benchmark values and the operator needs to follow the prescribed mitigation techniques for that particular parameter. Apart from this diagnostic function, the present section describes a range of practical measures aimed to improve solar farm efficiency by systematic benchmarking and operational review. The key actions include tracking degradation, improving inverter performance, reducing system losses, and maintaining grid stability. Optimising O&M through regular monitoring, timely maintenance, and effective grid coordination helps ensure reliable operation, lower downtime, and sustain high levels of energy output in the long-term.

4.4 Recommendations

Based on the benchmarking outcomes obtained from the SMART framework, targeted improvement strategies are proposed to address the identified performance limitations.

4.4.1 PV modules and inverters optimisation

Improving PV system performance and durability requires careful optimisation of modules and inverters. Durable materials, improved cell connections, and reliable encapsulation reduce long-term degradation. Using trackers to follow the sun increases energy capture, while modern, next-generation inverters reduce power waste during conversion. These steps ensure the system remains reliable and profitable for many years [35].

4.4.2 Cleaning and maintenance practices

Efficient cleaning and maintenance are pivotal in sustaining PV system performance. Dust and soiling significantly degrade PV module performance, and effective cleaning strategies. Integrating Internet of things (IoT) sensors enables predictive scheduling based on environmental. Regular visual inspections detect defects such as cracked cells and hotspots, preventing energy losses. Additionally, seasonally adjusting panel tilt angles enhances light capture. These strategies collectively maximise the output and system longevity [35].

4.4.3 Continuous monitoring

Continuous monitoring is essential to validate the effectiveness of optimisation strategies in a solar farm. Key performance indicators such as energy output, efficiency, and operational losses should be tracked for early detection of anomalies. This real-time data enables ongoing performance evaluation and supports refinement of operational strategies. This data-driven approach not only maximises plant output but also contributes to sector-wide learning and innovation through shared performance insights [35].

4.4.4 Innovation and emerging technologies

Innovative thermal management approaches, including both active and passive cooling, are critical for mitigating efficiency losses from overheating and slowing module degradation. Enhancing light absorption

via anti-reflective coatings and concentrating technologies further boosts energy capture. Emerging innovations like bifacial panels increase yield by capturing sunlight on both sides, especially over high-albedo surfaces. Additionally, AI-driven predictive maintenance optimises performance by minimising downtime and improving operational efficiency. These innovations collectively drive performance optimisation in next-generation solar PV systems [35].

4.4.5 Targeted strategies and benchmarking

This study proposes targeted mitigation strategies aligned with key performance parameters to enhance solar farm efficiency, as summarised in Table 1. While providing a foundational framework for performance assessment and efficiency enhancement, the study does not include empirical evaluation of specific plants. It offers a valuable basis for future research focused on advancing solar power plant optimisation.

4.4.6 Effective planning and best practices

Successful solar farm development requires systematic planning from site selection to long-term operation, supported by accurate resource assessment, grid analysis, and sound financial planning. Best practices prioritise the deployment of high-efficiency PV modules, robust mounting systems, premium components, and advanced inverters to maximise energy yield. Rigorous testing, skilled construction management, and sustainable practices such as PV module recycling and minimising environmental impact are essential for ensuring reliability and ecological responsibility. The SMART framework introduces a unified audit method that standardises performance indicators and enables consistent, practical evaluation across projects. This practical tool turns complex research into clear steps for reliable, long-term energy production.

5 Conclusions

This study presents the SMART framework as a structured and practical approach for improving the transparency, consistency, and effectiveness of energy auditing in utility-scale solar power plants. By consolidating verified performance indicators, benchmark thresholds, and mitigation strategies into a single operational methodology, the framework addresses the persistent gap between installed capacity and actual energy generation observed in many solar farms. Unlike conventional auditing practices that focus on isolated parameters or site-specific assessments, the SMART framework integrates preliminary diagnostics, detailed technical evaluation, and performance benchmarking into a reproducible process aligned with international standards. The application of standardised metrics such as PR, AY, CF, and degradation rate enables objective comparison across plants operating under different environmental and operational conditions. This structured approach allows inefficiencies related to thermal stress, inverter performance, grid interaction, and system losses to be identified and addressed systematically.

The framework is intentionally designed for scalability and field applicability. It relies on commonly available monitoring data and instruments, making it suitable for both newly commissioned and ageing solar installations without requiring major infrastructural changes. By directly linking audit outcomes to targeted corrective actions, the SMART framework supports informed maintenance planning, reduction of avoidable losses, and sustained improvement in energy yield. Conventional energy audits focus mainly on instantaneous performance indicators. The SMART framework goes further. It includes comprehensive auditing of technical performance, degradation assessment, and benchmarking parameters. This supports long-term condition monitoring and maintenance, planning and enables lifecycle management for utility-scale solar farms.

While this study focuses on framework development rather than plant-specific validation, it establishes a robust foundation for future empirical application and comparative performance studies. The SMART framework provides solar plant operators, consultants, engineers, and regulators with a practical auditing tool that transforms fragmented technical knowledge into a coherent decision support system, contributing to the long-term reliability and sustainability of large-scale solar power infrastructure.

Appendix A. Supplementary data

Supplementary data to this article can be found online at <https://doi.org/10.1016/j.jnlest.2026.100369>.

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Kaovinath Appalasamy: Writing—original draft, Conceptualization, Data curation, Investigation, Methodology, Resources, Software, Visualization. **Rizalman Mamat:** Writing—review & editing, Formal analysis, Funding acquisition, Project administration, Resources, Supervision, Validation. **Sudhakar Kumarasamy:** Writing—review & editing, Conceptualization, Formal analysis, Methodology, Project administration, Resources, Supervision, Validation.

Declaration of competing interests

The authors declare no conflicts of interest.

Use of AI tools declaration

During the preparation of this work, the author(s) used ChatGPT, Grammarly, Scopus AI and Google Gemini to improve the language and clarity of the text. After using the AI tool, the author(s) reviewed and edited the content as needed and took full responsibility for the publication's content.

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