INDONESIAN PV POWER PLANT PERFORMANCE: FAILURE-MODE ALIGNMENT WITH AN OPERATION AND MAINTENANCE ENHANCEMENT STRATEGY

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Towards a 2060 net-zero-emission target, Indonesia has had slow growth in its solar photovoltaic capacity; current installations are plagued by performance problems. Detecting failure modes and augmenting operation and maintenance strategies for reliability enhancement of solar power plants is this study's aim and, fills a regional research gap by identifying the local causes of underperformance of photovoltaic power plants, giving an O&M strategy to mitigate these problems. The methodology builds upon secondary research, low-yield case-study company reports, structured interviews with 4 key Indonesian solar industry experts and, a Pareto analysis to identify the 20% of components (invertor faults/ battery drop-offs) responsible for 80% of energy-yield deficits. Failure mode effects analysis then populates a developed, structured maintenance framework for Indonesian PV plants. This work shows that improvement in the general energy-yield of Indonesian photovoltaic power plants is addressed by targeted O&M, which enhances solar power plant performance in rural Indonesia, towards helping attain the country's objectives on renewable energy, adding to the overall goal of sustainable energy development in the region.

Keywords: PV-power; energy-yield; failure-modes; O&M-framework; Indonesia

Background: Indonesian Power Plant Problems

Solar photovoltaics have emerged as a promising renewable energy source in Indonesia, with the ability to meet the country's rising power needs, while decreasing dependency on fossil fuels. According to Indonesia's National General Energy Plan (RUEN 2017), the country has a renewable energy 'potential' of 443GigaWatts, with solar energy estimated at 208GW (within a global potential of 5kGWs); however, actual solar photovoltaic PV growth in Indonesia is slow compared to other countries, thus more realistic increases in solar PV are pegged at 5GW by 2030 (PLN 2021).

Solar energy systems once installed require little in terms of maintenance or attention (Bosman *et al.,* 2020), but this assertion stems from research conducted into the reliability monitoring and servicing of the PV cell panels and, does not recognise that an overarching system's actual measurable performance is often much lower than predicted energy-yields. This is the problem that currently occurs in Indonesia (Nasir

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2024), where declining performance (low expected yields) of installed solar power plants are being recorded, particularly in rural provinces such as East Nusa Tenggara.

It is argued that this underperformance of Indonesian PV Plant occurs because of inadequate operation and maintenance (O&M) programmes (Rukijkanpanich 2020) and that, ad-hoc preventive and corrective maintenance programmes and, a lack of structured condition-based predictive maintenance (Iftikhar 2021), lessens predicted energy-yields. Indonesia's problem is a lack of suitable operation and maintenance methodologies, thus solar energy systems face knock-on issues, such as reduced energy output, component malfunctions, and a decreased operational lifespan (Gonzalo 2020). Well-designed programmes for operation and maintenance are argued to help identify issues early then resolve them, reduce costs, and ensure better system yield-performance (Hernandez 2019). Reductions in generation yield presents challenges for the growth of Indonesia's solar energy sector and hence, represents an urgent need to focus on a better methodology for maintenance in rural Indonesian.

Current Solutions for Solar Power Plants and Gaps in Indonesian Provision

The underperformance of Indonesian solar power plants not only affects energy production itself but also impacts the economic viability predictions of future solar projects and the reliability of its grid, although, theoretical approaches can be sourced to optimise operational and maintenance efficiency in solar energy installations; one such approach is the implementation of preventive maintenance programmes, regular inspections and proactive maintenance activities to identify and address issues early (Iftikhar 2021) such as: Cleaning panels, addressing electrical issues, and monitoring system performance. Other countermeasures include advanced maintenance strategies, such as predictive maintenance utilising sensor data, together with machine learning and other forms of analysis in searching for potential problems and, therefore scheduling maintenance on predictive outcomes (Bosman 2020).

Although valuable understanding has emerged for effective implementation of O&M practices for solar power plants, these approaches are uncommon in rural Indonesia, which needs a (currently lacking) user-friendly maintenance structure. The framework developed here addresses this pressing gap and outlines the key factors for decreased yields and offers a maintenance framework for O&M practices at PV plants; it applies Pareto's 80-20 principle (Kenton 2024) to identify key failures within a case-study with performance problems, in East Nusa Tenggara. To determine such causes, effects and mitigations of low energy-yields, a failure-mode and effects-analysis (FMEA) can rank plant variables and, suggest maintenance procedures of predictive, preventive, corrective, and condition-based. The goal here is to create a maintenance framework to mitigate critical failures by O&M activities. The 6 objectives of this work are:

1. review literature to identify of global trends, in solar power plant O&M.
2. investigate company reports that identify yield prediction-anomaly factors.
3. catalogue this case-study's solar PV failure modes and performance-decline factors.
4. conduct Pareto analysis of the key components that result in 80% of its poor-yield.
5. determine the causes, effects, and mitigation strategies by FMEA, and through a qualitative methodology to blend insights from 4 Indonesian PV expert stakeholders.

6. Validate (by expert-interview) a 'maintenance-framework' for the PV industry in (rural) Indonesia and thus, fill the current gap for a structured O&M approach.

Overview: Research Addressing Indonesian Solar Sector Efficiencies

This research deals the Indonesian solar energy industry's inadequate operational and maintenance routines that affect the efficiency of its existing facilities. While there is great solar resource potential of 200GW, current installed capacity amounts to only 0.2 GW, thus capacity-yield lags far behind solar potential (DENBEN 2020). This work seeks to improve solar plants' energy-yield by enhancing maintenance strategies.

Secondary Research: Plant Failure and Monitoring

Towards objective 1 and 2 above, a literature review of failure modes, PV performance and degradation mechanisms affecting solar power facilities, a synthesis of current practices and strategies for condition monitoring and predictive maintenance, follows:

Failure Modes of Photovoltaic Power Plants Globally: Indonesian Implications

Lorenzo's (2020) study of 80 large PV plants in Italy examined common failures and unexpected events in PV systems but was unable to find solutions to address diverse issues such as site instability, weather events and blown combiner-box string fuses. Iftikhar's (2021) research then postulated if simple O&M practices, performed by plant personnel themselves, with support from combining field data with simulated results, can increase energy yields (in 18-megawatt photovoltaic) grid-connected PV power plants and, although able to show that tracker-systems inverters and combiner-box malfunctioning do cause internal shutdowns and reduced energy output, he found current ad-hoc O&M approaches were ineffectual. Colli (2015) asked if a FMEA scoring system of severity, occurrence, risk and detection ratings, developed for a PV system, improves power yield but again found no causative improvement. Similarly, Triki-Lahiani's (2018) investigation of fault detection and monitoring and failures, occurring within PV systems, found that whilst PV systems experience failures that do reduce PV installation's reliability, no O&M solutions are available. Sarr's (2017) PV system failure work is in line with Colli (2015), in which applied FMEA can improve maintenance of PVs but need a targeted approach.

It is argued here that the current work has not analysed actual failure reports from site, using techniques like Pareto analysis to identify the critical failure modes contributing to the underperformance of PV power plants; indeed, there is no work looking at the failure modes of PV power plants in Indonesia. Therefore, this study aims to fill this research gap by conducting detailed analyses of failure data from PV power plants, using a case-study approach in the East Nusa Tenggara province of Indonesia, by applying Pareto analysis and a failure mode effects analysis (FMEA) method.

(Under)Performance Issues and Degradation Mechanisms of Solar Power Plants

Oh's (2018) longitudinal failure analysis of a Korean PV power plant indicated that the actual system yield output is 10% less than a nameplate/predicted capacity (via inverter losses). Relatedly, Iftikhar (2022) found that 5% underperformance of a PV plant faced an estimated yearly monetary loss of €175,000, but that predictive maintenance may reduce this. Baschel's (2018) work also looked at how reliability affects operation, and proposed strategies for improving maintenance and reducing downtime to enhance energy yield, by targeting local system components of transformers and inverters, as these contribute to two-thirds of the total energy losses due to their long lead/repair time, finding that even a small number of issues with

transformers lead to big energy losses. Underperformance in solar photovoltaic power plants can be derived from identifiable failure modes and degradation mechanisms. The Korean, Spanish, and Italian studies above inform this work's East Nusa Tenggara PV power plant's actual failure data and, help develop this regional O&M framework.

Condition Monitoring of PV Plant: Applications to Inform Indonesia
Globally, analytical condition monitoring systems are deployed to identify PV system malfunction (Betti 2019). Lorenzo's (2020) remote monitoring O&M techniques use data from Italian PV Plants targeting combiner-box analytics for fault detection and improved maintenance. Livera's (2022) decision support system (DSS) also monitor systems' early fault diagnosis in cloud-based platforms, where losses of 2100MWh or 14% of energy output, can then recover 7% of lost energy, by corrective, field mitigation activities. Indeed Abdulla's (2024) bibliometric analysis and systematic literature review of 186 articles found that maintenance strategies stemming from performance indicators and degradation modelling can lead to better O&M and thence energy-loss improvements. However, these reviewed studies have not discussed the potential of a centre-controlled remote condition monitoring, which is required for photo-voltaic (PV) systems, located in remote regions that are limited by accessibility and poor network connectivity, and based on this research gap, the present study is deemed necessary for Indonesia's multitude of islands and remote locations.

Predictive Maintenance of Solar Power Plants
Orosz (2024) summarised the challenges regarding operability and maintainability of solar power installations to highlight economic and technical relevance as contributory to increased efficiency and maintenance strategies, suggesting that advanced monitoring and AI and IoT-based diagnostic tools are needed. Bosman (2020) argued for third-party, system-level predictive maintenance tech applications but, notes that these still need manual diagnostics, failure modes and effects analysis and, machine learning through real-time analysis. Triki-lahiani's (2018) finds that again (advanced AI) monitoring techniques as crucial for the early detection of faults and the optimisation of performance. However, reviewed studies focus on developed nations' applications, and are less applicable to newly developing regions' distinct geographic and infrastructural constraints. The following method presents a way to fill this gap.

METHOD

This work adopts a qualitative, case-study approach to explore the operation and maintenance challenges faced by solar power plants in East Nusa Tenggara, to develop a maintenance framework for optimal operation in the localised PV industry. It draws on in-depth interviews with key stakeholders in the country's solar sector. This qualitative methodology gives understanding of the complex issues and contextual elements influencing solar power facility performance; the 4 expert practitioners' life-experience/ phenomenological reflections exhibit a grounded (saturation) of issues and therefore presents an appropriate sample (Creswell 2018).

The case-study is selected as it typifies the performance degradation in PV power plants in East Nusa Tenggara, Indonesia and thus can identify factors for low yield.

Qualitative Research Semi-Structured Interviews' Participants' Selection
Semi-structured interviews conducted with local PV stakeholders in Nusa Tenggara and Jakarta, inform the development of a new maintenance framework. Compliant with Creswell's (2018) life-experiences' quorum, they are: An Operations-Manager with direct experience operating and managing solar power plants; a Maintenance-

Manager with responsibility for implementing maintenance programmes and addressing performance issues for solar power plants; an Assistant-Manager-in-power-plant-evaluation charged to monitor power plant daily operations, evaluate equipment's' performance and create monthly generation reports; and, a PV power plant expert with in-depth technical knowledge of solar power system design, installation, and maintenance. 3 manager interviews were done face-to-face on-site; 1 virtual 'Teams' interview was conducted with the Jakarta based PV-expert. Accurate capture and preservation of the data followed overarching West Australian (WA) guidance(s) for datasets that log respective interviewee perspectives and insights.

Data Analysis, Validity and, Ethics

The semi-structured interviews use a thematic analysis methodology to discover and interpret recurring themes (Naeem 2023). The 28 questions posed built on secondary research. For this research of PV performance degradation, validity was done by cross checking responses by re-interviewing the 4th, PV-expert participant who also validity-checked the developed, maintenance framework. Respondent-confidentiality, right-to-consent, psychological-wellness, recruitment-material and data-management were pre-approved by the WA Ethics committee. The case-study's historical, documented failure-reports allowed a ranking of failure-modes using Pareto Analysis.

RESULTS

Pareto Analysis and Qualitative Data

Located on Mules Island in the Savu-Sea, this off-grid PV power plant in East Nusa Tenggara, Indonesia comprises panels, inverters, AC-distribution, LVMDP-panels, transformer, MV-cubicle and battery-systems. Five years of documented failure-events' reports (Sep 2019 - Feb2024) identify 24 key performance issues. Analyses of cumulative failure-modes is assessed by a Pareto analysis; resultantly, five critical issues, from the historical 24 items, can be stated in Table 1 and, Figure 1.

Table 1: Pareto tabulation of failure modes: Generated from 24+ key recurrencies (2019-24)

Recorded failure causes	#	Cumulative Total	Cumulative %
Battery drop-off	10	10	42%
Inverter Fault	10	20	83%
Inverter fan faulty	2	22	92%
MCCB Combiner Burnt	1	23	96%
UPS battery broken	1	24	100%

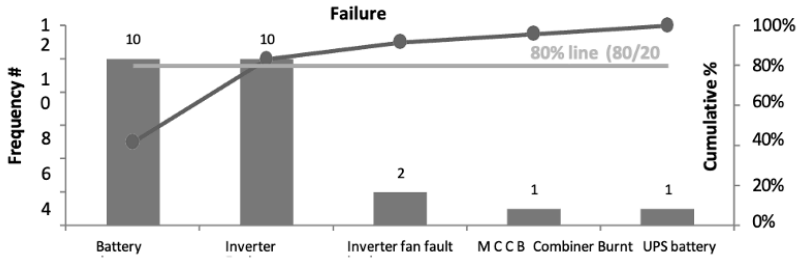

Figure 1: Pareto graphic of failure modes: Generated from 24+ key recurrencies (2019-24)

Pareto analysis identifies the top failure modes as: Battery-drop and inverter-fault.

Qualitative Results Respondents' Data-set Correlation Highlights.

Semi-structured interviews with 4 participants display role-perspectives. Correlation highlights linking to plant faults include Responses to Question 24 of 28 seeking

suggestions to mitigate plant failures. Respondant-1 said there's a need to "monitor battery temperature", whilst R-2 said, "inventor grid connections need constant updates"; R-4 argues for an "inventory of critical battery spare parts to minimise downtime during replacement". Asked if current advanced tech. might help maintenance (Q.25 of 28), R2 said "we must implement predictive maintenance through continuous data analysis of the most important items". Asked (Q.27) if O&M tools improve performance, R2 said "yes but make sure they connect to the entire enterprise-asset-management systems, so systems can action automatically, but we know this does not happen". R3 states that "predictive maintenance O&M tools are proven overseas for optimising PV plant performance, so we should also have this"

DISCUSSION

O&M Practices, Failure and Funding

This section discusses key findings (and comparisons with literature), highlighting gaps in knowledge, and outlining the implications for Indonesian sector best practice.

Insufficient O&M Practices and Critical Failure Modes

The interviews conducted with four participants indicate a consensus that there's a lack of supervision and maintenance that contributes to a decrease in the production of electricity from PVs in rural Indonesia. This aligns with existing literature on performance and maintenance issues of PV plants, that simple and efficient O&M practices optimise the energy output (Iftikhar 2021). Insight into the elements contributing to the deterioration in the performance of PV power plants finds a recurring theme from the responses that the battery energy storage system BESS and Inverter are the primary sources of problems in performance issues. The existing strategies directed toward overcoming these deficiencies, consist essentially of both preventive and corrective maintenance. Nevertheless, all participants agree that these strategies are inadequate and need improvement. This agreement underlines the considerable gap between current maintenance practice and, the attention needed.

Insufficient Funding and Training and, Local Technology Deficits

The interviews reveal a consistent theme of insufficient funding and training as a major hindrance to effectively addressing PV plant degradation, aligning with existing literature (Rediske 2022). The interviews reveal a need for a more comprehensive cost-benefit analysis of the different options for O&M strategies in diverse rural locals. Higher degradation rates mean less electricity yield, while associated shorter lifespans negatively impact the project's overall economic viability. Therefore, potential opportunities for investing in this technology may likely reduce in less populated or developing regions, where demand for renewable energy alternatives is often at its greatest. Inadequate training or upgrading of skills for maintenance staff, especially in remote locations, may result in a circle of inefficiency - improper skill-sets mean staff cannot maintain plant effectively, resulting in increased failure.

The semi-structured interviews with the four participants reveal a consistent theme of limited technological resources for maintenance strategies in PV power plants, specifically in remote locations. All participants highlight that current methodologies for performing maintenance rely on very basic technologies and indicate a large gap between the discussions of advanced technologies of scholarly literature and their deployment in remote photovoltaic power plants. This inconsistency underlines a critical gap in knowledge on how to adapt high-level tech. for remoteness and locals with resource constraints. The prevailing need is for research contributions to cost-effective, easily implementable monitoring solutions' structures and frameworks.

CONCLUSIONS

Addressing Underperformance

It is concluded that the main reason behind the degradation in performance of the Nuca Molas PV power facility is inadequate O&M strategies, and specifically: A lack of strategies concerning preventive maintenance and predictive failure analysis; access to higher levels of tech. and maintenance capabilities are limited in remote locations; insufficient training and capacity building for plant maintenance staff; and inadequate financial and human resources allocated to operation and maintenance activities.

These factors lead to more frequent unexpected failures, longer downtimes, and reduced overall efficiency that impacts the economic viability of rural PV power plant adoption. Recommendations for longer-term sustainability to address this follow.

Five recommendations to Enhance rural PV plants

This work presents the following Five-Recommendations to enhance O&M for rural solar photovoltaic power plants in Indonesia and, Nusa Tenggara Timur in particular:

Firstly - develop and implement comprehensive maintenance programmes. To address insufficient operation and maintenance practices, it is recommended that PV power plant operators implement a comprehensive maintenance strategy, namely: Develop a detailed schedule of check-ups, cleaning, and maintenance of all system components; Prioritise the critical components of Battery Energy Storage System and inverters; Implement cleaning procedures for panels to mitigate particulate-matter soiling; Create detailed standard-operating-procedures with detailed step-by-step guides for frequent tasks; and, Regularly record operational data and maintenance activities.

Secondly - enhance capacity building and training programmes for maintenance staff that includes hands-on training in installation, troubleshooting, repair, and preventive maintenance techniques. Online courses or periodic in-house training sessions need to include equipment manufacturers' specialised instructions for major components like BESS and inverters. Investing in the continuous professional development of maintenance teams is needed to empower their long-term performance activities.

Thirdly - a key recommendation here is relay of a (Pareto inspired) FMEA guide to mitigate critical PV failure modes analysis, from 5 years of company failure-reports and, in-depth interviews with the key stakeholders, Table-2 summarises the FMEA:

Table 2: Failure Mode and Effects Analysis - FMEA - critical failure modes' brief-summary

Item	Functional Failure effect	Failure Mode	cause	Improvement
Battery Storage System	reduced power output: Energy output nil	Battery drops	Extreme temp; low quality material; unit mischarge; controller issues	period inspection; monitor temp; routine clean; keep record; fit-for-use specs; charge optimise; spare parts inventories re downtime
Inverter	energy output nil	Inverter breaks	Bad vent; high temp; card/board overheats; overcurrent; software failure; protective relay miss-trips	period inspection; overheating checks; ventilate & cool; monitor grid connection & power quality; update firmware calibration; protect relay systems.

Recommendation-4: While there's increased capex/ upfront costs for condition-based monitoring and predictive maintenance technologies, these are recommended as they will lead to cost savings by reducing 'unexpected' failures and enhancing performance.

Recommendation-5: The 'maintenance-framework' (Figure 2) developed here is recommended for uptake by managers to enhance the reliability of rural PV systems.

Framework validation, by Respondent-4 of this work, argues that the East Nusa Tenggara PV plant generates 95,000,000kWh. With no action, future system failures and yields will decrease 8%, with a loss of 7,600,000 kWh (a revenue loss of Aus$1m); however, if the maintenance-framework's failure-detection is utilised (Figure 2) then production will decrease at the lesser rate of 4%, with 4,750,000kWh of energy recovered, generating a saving of Aus$0.6m. The deliverable developed here, the Maintenance-Framework (Figure 2); uptake is recommended.

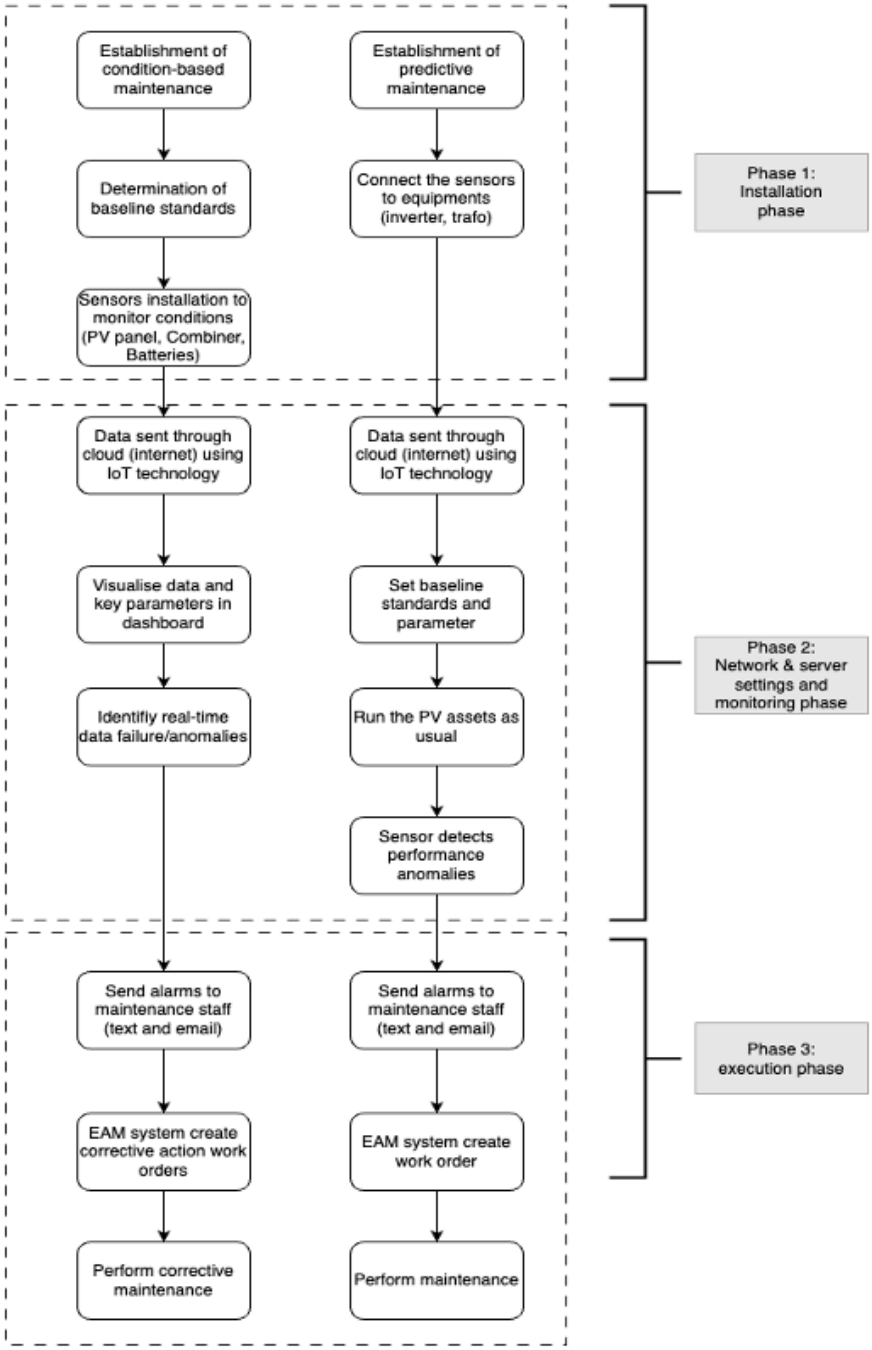

Figure 2: Maintenance-Framework: From Qualitative Research and Document Analysis

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