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IDENTIFYING RISKS FOR EFFECTIVE MAINTENANCE OF RENEWABLE ENERGY PLANTS IN THE NEW GREEN CAPITAL CITY OF INDONESIA

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This study explores the use of Failure Mode and Effects Analysis (FMEA) to identify and mitigate risks in Solar Power Plants (PLTS) in Indonesia's new National Capital City (IKN). As renewable energy is vital to Indonesia's sustainability goals, managing risks in PLTS is essential for ensuring reliable and efficient energy production.

The research identifies key challenges such as PV Array module failures, shading effects, and control system disruptions, which significantly impact electricity generation. Using the Risk Priority Number (RPN) methodology, the study ranks PV Array modules as the highest risk component (RPN 192), followed by Control and Management Systems (RPN 140) and PV Circuit Breakers and Video Monitoring Systems (RPN 120). These findings underline the need for targeted mitigation strategies.

Recommendations include regular PV module inspections, hotspot monitoring technology, firmware updates, and enhanced fire protection systems. Preventive measures like grounding current maintenance and fire sensor upgrades further minimize operational disruptions, ensuring component durability and system efficiency.

By leveraging the FMEA framework, this study systematically identifies and prioritizes risks while providing actionable solutions to enhance operational resilience. The results align with Indonesia's vision of achieving 80 % renewable energy utilization in IKN by 2045.

This research offers broader applicability for renewable energy systems in similar contexts, contributing to clean energy initiatives, reducing fossil fuel dependency, and supporting sustainable urban planning. It serves as a critical resource for integrating renewable energy into Indonesia's green and resilient capital city vision

Keywords: solar power plant (PLTS), failure mode and effects analysis (FMEA), asset management, risk analysis

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1. Introduction

Renewable energy systems, especially solar power plants (PLTS), have become crucial in the global transition towards sustainable energy solutions. In Indonesia, with abundant solar resources and increasing energy demand, the implementation of PLTS is essential to achieve long-term energy sustainability. However, operational complexity and potential system failures pose significant risks to reliability and efficiency. Key components such as PV arrays, inverters, and fire protection systems are prone to failure, which can result in energy loss and expensive maintenance costs. Despite advances in renewable energy technology, systematic risk identification and mitigation in PLTS systems remain underexplored, especially in the context of Indonesia's new National Capital City (IKN), which aims to lead the nation's green energy transition. Indonesia has just moved its National Capital to East Kalimantan and the relocation of the capital city to the Archipelago is also a joint effort in transforming the electricity system that is oriented towards the future. So that the Archipelago can become a city built with a reliable electricity system based on clean renewable energy, affordable with the principle of value for money, and sustainable prime services. The PLTS system, which was inaugurated in 2023, is currently still in its early stages, so it still requires many parties involved in evaluating the program being run.

The relevance of this topic lies not only in addressing technical challenges but also in supporting Indonesia's commitment to utilizing renewable energy. As the country targets 80 % renewable energy adoption in the IKN by 2045, ensuring the operational resilience of the PLTS system is very important. Existing literature highlights the benefits of renewable energy but lacks comprehensive insight into risk management methodologies tailored to PLTS. The Failure Mode and Effect Analysis (FMEA) approach offers a structured framework for identifying, evaluating, and mitigating these risks, making it an important focus for further research. Addressing this gap is necessary to improve system reliability, optimize resource allocation, and achieve Indonesia's green development vision.

Given the urgency to ensure energy security and reduce dependence on fossil fuels, research on PLTS risk analysis is timely and urgently needed. By identifying critical vulnerabilities and proposing effective mitigation strategies, this study addresses pressing scientific and practical issues. Consequently, developing a robust risk management framework for PV systems is a relevant and necessary effort to support Indonesia's sustainable energy ambitions and inspire similar progress in other regions facing similar challenges.

The Ministry of Environment and Forestry does not fully address the main aspects in the development of climate change mitigation and adaptation policy. The Ministry of National Development Planning is responsible for implementing the president's vision related to reducing energy intensity, decreasing greenhouse gas emissions and expanding the use of renewable energy. The National Energy Board oversees the implementation of the national energy policy with a cross-sectoral approach. The following is an institutional mapping of the energy sector in Indonesia [1].

2. Literature review and problem statement

The paper [2] explores the use of failure mode and effects analysis (FMEA) in solar photovoltaic (PV) systems. FMEA helps identify failure modes, effects, and corrective actions of PV components. The work explains that FMEA is a useful tool to ensure that PV systems are operating as intended. However, there are several unresolved issues related to accurately identifying PV system failure modes. Standards for severity, occurrence, and detection may not be sufficient to identify the underlying problem. This may be because more comprehensive data collection and analysis methods are needed to account for factors beyond standard measurements. One way to overcome this difficulty is to develop a common approach that combines quantitative and qualitative data from multiple sources.

The paper [3] presents the results of research on characterizing visual defects on installed solar photovoltaic (PV) modules in different climatic zones in Ghana. It is shown, that visual defects on PV modules depend on climatic conditions and hence, vary from one country to another. But there were unresolved issues related to the degradation rates of the modules with visual defects and those without visual defects. A way to overcome these difficulties can be to determine the influence of the visual defects on output power degradation of the modules. This approach was used in the study, however, there is no clear link between the observed visual defects and the PV module electrical performance since PV modules with severe visual defects could show low degradation rates and vice versa. All this suggests that it is advisable to conduct a study on an improved methodology for assessing the performance of PV modules that considers both visual and non-visual defects.

The research detailed in [4] explores a modified Failure Mode and Effects Analysis (FMEA) framework specifically designed for smart manufacturing settings. It has been demonstrated that the inclusion of a fourth factor – dependency (D2) in the Risk Priority Number (RPN) calculation of traditional FMEA significantly improves the detection and prioritization of vulnerabilities in components related to Industry 4.0 (I4.0), including proximity sensors and color contrast sensors. Nonetheless, challenges remain concerning the complexity and expense of conducting thorough assessments for I4.0 systems. This may stem from inherent difficulties in integrating advanced technical elements (such as sensors and IoT modules), the fundamental constraints in standardizing evaluations across various systems, and the substantial costs associated with developing preventive strategies, rendering pertinent research both challenging and resource-demanding. A way to overcome these difficulties can be combining traditional risk assessment methods with advanced data analytics, allowing for a more adaptive and predictive approach to maintenance. All this suggests that it is advisable to conduct a study on how to adapt enhanced FMEA techniques to renewable energy plants in a green capital city context. This would address unique challenges such as diverse environmental conditions, lifecycle cost optimization, and technology integration for predictive maintenance, ensuring operational resilience and sustainability.

The research detailed in [5] focuses on assessing the risks associated with an integrated photovoltaic-thermal-fuel cell (IPVTFC) system through classical analyses of failure modes, effects, and criticality. The findings indicate that the risk priority numbers for the absence of solar radiation, hydrogen leakage, photovoltaic module failure, and oxygen leakage were 450, 270, 240, and 240, respectively. Correspondingly, their criticality values were 90, 54, 80, and 48. However, challenges remain in accurately evaluating the risk of hydrogen leakage. This may stem from the necessity for more thorough data collection and analytical methods that take into account a range of factors beyond conventional ratings. Developing a generalized approach that integrates both qualitative and quantitative data from diverse sources, such as field data, test results, literature, and expert insights, could help address these challenges. This approach was used in previous research, however, it has certain limitations. All this suggests that it is advisable to conduct a study on an improved methodology for assessing the risk of hydrogen leakage that considers various factors beyond standard ratings.

The study outlined in [6] explores the analysis of risk priority numbers (RPN) to assess the severity of failure modes in photovoltaic (PV) systems and their effects on performance decline. It has been demonstrated that RPN analysis is utilized to determine the criticality of failure modes impacting the performance of c-Si technologies. However, certain issues remain unresolved regarding degradation modes, including hot spots and de-lamination, which pose safety concerns with RPN values falling below 50. This might be attributed to the necessity for more thorough data collection and analytical approaches that take into account a range of factors beyond conventional ratings. One method to address these challenges is to create a generalized strategy that integrates qualitative and quantitative information from multiple sources, such as field data, test data, literature data, and expert insights. While this approach has been utilized in earlier studies, it does come with specific limitations. All this suggests that it is advisable to conduct a study on an improved methodology for assessing the RPN of PV modules that considers various factors beyond standard ratings.

The paper [7] presents a review of research publications on rooftop photovoltaic systems, analyzing their potential for power generation and carbon emission reduction. It is shown that the installation angle, tracking system, mechanical properties, shielding effects, indoor effects, and life cycle of photovoltaic modules all play a significant role in the efficiency of these systems. But there were unresolved issues related to the performance of PV modules under the impact of the external environment during long-term outdoor operation. The reason for this may be that most research results come from theoretical calculations and short-term experiments in the laboratory, while the long-term measured results of PV systems in use are still lacking. A way to overcome these difficulties can be to conduct more long-term studies and collect more measured data from actual PV systems in use. This approach was used in some research, however, the challenge of accurately predicting the performance of PV modules under the impact of various external factors over a long period remains.

The previous papers share similarities in applying Failure Mode and Effects Analysis (FMEA) to evaluate risks placing once again emphasis on the Risk Priority Number (RPN) for ordering the mitigations, same with [8]. Both indeed place an emphasis on the importance of qualitative status and quantitative information on risk analysis but also on contextual variability such as environment considerations for PV systems or particular production conditions. Nevertheless, key differences arise in scope and application: the focus of the journal is on how to maximize the efficiency of inspection processes in order to reduce the risk of product nonconformity, whereas the other works consider more wide-ranging aspects such as PV module visual defects, H2 leakage in IPVTFC systems, and the impact of mid- and long-term environment on the performance of rooftop PV systems. In this context, adding more analytics as outlined in [4, 6] may improve the actual use of the proposed methods in the scope of the journal.

This study enhances the FMEA method for analyzing the risk of failure in the IKN PLTS system. Previous studies have applied FMEA in various fields, such as: Ensuring the smooth operation of PV systems; Assessing the performance of PV modules with visual and non-visual defects; Improving the detection and prioritization of vulnerabilities in components related to Industry 4.0; Evaluating the risk of an integrated photovoltaic-thermal-fuel cell (IPVTFC) system; Assessing the severity of failure modes in photovoltaic (PV) systems and their effects on performance decline and Analyzing the potential for power generation and carbon emission reduction of rooftop photovoltaic systems.

By systematically calculating the Risk Priority Number (RPN) for critical PLTS components such as PV arrays, inverters, and control systems, this study addresses the unresolved issue of operational inefficiencies and failure risks in solar power systems within Indonesia's new National Capital City (IKN). The research identifies and prioritizes failure modes based on their severity, occurrence, and detection, offering a structured approach to mitigate these risks. This is particularly critical given the local challenges of maintaining resilience in renewable energy infrastructure amidst Indonesia's ambitious green energy targets. The findings provide actionable insights into enhancing system reliability and sustainability, aligning with the nation's vision of a renewable-driven, resilient capital city. By bridging existing gaps in risk management strategies, this study contributes to addressing the broader issue of operational vulnerabilities in PLTS systems, which is crucial for achieving long-term energy efficiency and sustainability goals.

3. The aim and objectives of the study

The aim of the study is to identify potential risks in Solar Power Plants (PLTS) within Indonesia's new National Capital City (IKN) using the Failure Mode and Effects Analysis (FMEA) framework. This will ensure operational resilience, efficiency, and alignment with the nation's renewable energy goals.

To achieve this aim, the following objectives are accomplished:

– to identify and classify potential failure modes in critical PLTS components such as PV arrays, inverters, and control systems;

– to evaluate the severity, occurrence, and detection of each failure mode and calculate their Risk Priority Numbers (RPN) to prioritize mitigation efforts;

– to develop actionable recommendations for risk mitigation, including preventive maintenance strategies and technological upgrades, to enhance the reliability and sustainability of the PLTS system.

4. Material and methods

The subject of this study is the objectives concerning the Solar Power Plant system (PLTS) functioning within the scope of the new National Capital City of Indonesia (IKN) – its critical component(s)'s failure risk mitigation options. The PLTS system's systematic strategic investment planning is proposed to be improved as a result of enhanced reliability, operational resilience, and sustainability of the system in order to comply with Indonesia's renewable energy targets, which is the main thesis of this research work.

The study considers that historical data and expert judgment are reliable sources for estimating the realistic likelihood of failures. All critical components analyzed (PV Arrays, Inverters, Circuit Breakers, Transformers, MV Distribution Systems, Fire Protection Systems, Grounding Systems, Video Monitoring Systems, and Control and Management Systems) from a systems perspective are integrated and influence system performance. This is the main basis for describing the essence of this work, which covers the characteristics of the problem studied. All critical failure modes for each component are evaluated to the most significant mode in order to decrease the level of detail of the analysis. Elements of the FMEA methodology assume an unchanged operational regime, excluding severe and completely destructive things like extreme accidents or natural disasters. So Detection (D) measures are taken into account based on the currently most effective monitoring systems and technologies available on the market today.

This study employs a quantitative descriptive approach combined with the Failure Mode and Effects Analysis (FMEA) methodology to systematically identify and assess potential risks in the PLTS system. Data is obtained from key operational assets and technical specifications of the PV system components. The FMEA framework is used to systematically identify potential failure modes in each component and evaluate them based on three parameters:

1. Severity (S) – Measures the impact of failure on the overall system performance.

2. Occurrence (O) – Estimates the likelihood of failure based on historical data and expert judgment.

3. Detection (D) – Assesses the ability to detect potential failures before they occur.

The Risk Priority Number (RPN) is calculated by multiplying these parameters (RPN=S×O×D) to prioritize risks and identify critical components requiring immediate attention.

After conducting the FMEA Analysis, the next step is to verify the results by comparing the findings with operational practices or industry standards and identify the highest RPN value to determine the urgency. Through matter, the researcher will recommend risk mitigation and system improvement strategies for more optimal results. Here is an overview of the method research conducted by the researcher: to systematically identify and assess potential risks within the IKN PLTS, this study adopts the Failure Modes and Effects Analysis (FMEA) methodology, as illustrated in Fig. 1. This structured approach facilitates a comprehensive evaluation of each component within the PLTS, ensuring that potential failures and their impacts are thoroughly understood.

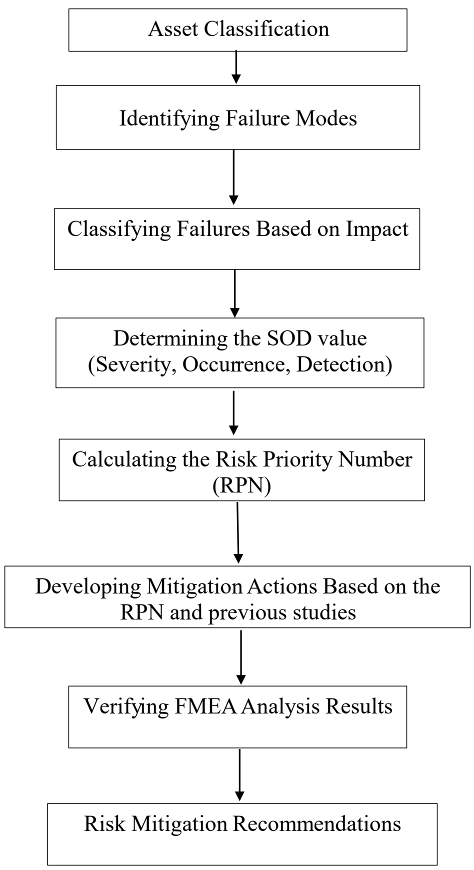

Fig. 1. Methodology study

As depicted in Fig. 1, the FMEA process begins with asset classification, followed by identifying potential failure modes for each asset. These failures are then classified based on their potential impact on the overall system. The severity (S), occurrence (O), and detection (D) of each failure mode are assessed, leading to the calculation of a Risk Priority Number (RPN). This RPN allows for prioritization of the most critical failure modes, enabling focused mitigation efforts. Based on the RPN values and insights from previous studies, mitigation actions are developed and subsequently verified to ensure their effectiveness. This systematic process culminates in the formulation of risk mitigation recommendations, providing a robust framework for enhancing the reliability and resilience of the IKN PLTS.

5. Results of the risk analysis in PLTS systems

5. 1. Identification and classification of failure modes in critical PLTS components

The Indonesian government is committed to realizing a green and environmentally friendly National Capital City (IKN) environment, utilizing renewable energy, especially Solar Power Plant (PLTS) with a capacity of 50 MW. The PLTS, planned to be built on a 100-hectare site in the Sepaku District, East Kalimantan, is expected to meet 10 % of the IKN's electricity needs. This project includes a 10 MW PLTS, which has been scheduled for commercial operation in early 2024, followed by a 40 MW PLTS, slated for operation in mid-2024. The government's long-term plan is to ensure that 80 % of the IKN's electricity needs are met through new and renewable energy (EBT) by 2045. In tandem with the PLTS construction, infrastructure development includes a 50 MW substation to provide a consistent electricity supply throughout the plant's installation process. In addition, natural gas is also used as a clean energy source for IKN, with the scheme that has been approved by the Ministry of Energy and Mineral Resources and the Pertamina Group [9].

Based on the data from the website, currently the PLTS built in Pemaluan Village, East Kalimantan, has generated 10 MW out of the total target of 50 MW, which is scheduled to be completed by the end of 2024. With 21,600 solar panels installed in an area of 80 hectares, the project not only meets electricity needs for the State Palace and the governance center, but also contributes to reducing fossil energy dependence and carbon emissions. PLN is committed to finishing the installation of additional panels to reach full capacity, supporting the government's plan so that 80 % of the IKN's electricity needs come from new and renewable energy by 2045 [10].

Given the government's urgency, the writer tries to analyze the failure risks of the PLTS system during operation. The IKN PLTS consists of 9,959 equipment assets. Then the researcher tries to classify types of PLTS assets based on a number of classification assets involved in the renewable energy system, especially photovoltaic system (PV). The basis for determining the asset classification is RDS-PP [1]. Every listed asset plays an important role in ensuring operational efficiency and safety. This classification covers various components, starting from the PV generator to the monitoring system, which ensures optimal energy management and distribution. Here is the classification standard for the total assets of Photovoltaic Power Plants and Photovoltaic Craftworks: to ensure a systematic analysis of the IKN PLTS, a clear classification of the system's assets is necessary. Table 1 provides a comprehensive breakdown of the main system and subsystem codes, adapted from the RDS PP. This classification helps in structuring the FMEA and ensuring all critical components are included in the analysis.

Table 1

Main system and subsystem codes

Code letter of the book of records	Denomination
A_	Electrical grid and distribution systems
AH_	Systems for 30 kV $< Un <$ 45 kV
AHA	33 kV delivery distribution
AHQ	33 kV field distribution
M_	Energy conversion (without heat generation) and transmission systems
MQ_	Photovoltaic systems
MQA	Photovoltaic generator systems
MQY	Control and protection systems
MS_	Systems to lead out electric energy
MSC	Systems to switch electric energy (generator circuit breaker)
MSE	Systems to invert electric energy (inverters)
MST	Systems to transform electric energy (unit transformers)

Table 1 categorizes the IKN PLTS into key areas such as electrical grid and distribution systems (A), energy conversion and transmission systems (M), and systems for leading out electric energy (MS). Further sub-classifications, such as photovoltaic systems (MQ) and their components like photovoltaic generator systems (MQA) and control systems (MQY), allow for a granular analysis of potential failure modes within each specific area.

In addition to the main systems and subsystems, the IKN PLTS also incorporates auxiliary systems that play a crucial role in overall operation and safety. Table 2 outlines these systems and their corresponding codes, providing a comprehensive overview of their functions within the PLTS.

Effective control and management are vital for ensuring the safe and efficient operation of the IKN PLTS. Table 3 provides a detailed classification of the control and management systems employed within the PLTS, drawn from the Book of Records. This classification aids in understanding the hierarchical structure and functions of these crucial systems.

Table 2

System addition for network and distribution

Code letter of the book of records	Denomination
A_	Electrical grid and distribution systems
A X_	Systems for fulfilling auxiliary purposes or task
A X B	Fire protection systems
A X C	Electrical installation
AXF	Ventilation systems

Table 3

System central control and management

Code letter of the book of records	Denomination
C_	Control and management systems
CB_	Operation and monitoring
CBA	Operation and monitoring A
CC_	Automatic systems
CCA	Automatic systems A
CF_	Data transfer and remote control systems
CFA	Data transfer systems A
CK_	Process monitoring
CKA	Fire alarm systems
CKC	Video monitoring

As shown in Table 3, the control and management systems, categorized under code 'C', encompass various functions such as operation and monitoring (CB), automatic systems (CC), data transfer and remote control (CF), and process monitoring (CK). Further sub-classifications, like fire alarm systems (CKA) and video monitoring (CKC), highlight the comprehensive nature of the control systems in place. By explicitly defining these systems within the FMEA framework, the analysis can assess the risk associated with potential failures in control and monitoring mechanisms. This ensures that mitigation strategies not only address physical components but also the critical systems that govern their operation. This holistic approach enhances the reliability and safety of the IKN PLTS by safeguarding its operational integrity.

From the classification standard for Photovoltaic Power Plants and Photovoltaic Craftworks, the researchers limit the analysis to assets related to PLTS, defining the classification of assets used in the study. This can be seen in the following Table 4.

The first step in conducting the FMEA involves classifying the assets within the IKN PLTS. This classification ensures a systematic approach to identifying and analyzing potential failure modes. Table 4 presents a comprehensive list of assets, their corresponding RDS-PP codes (referencing the system used for asset management), and a brief description of their functions within the PLTS.

Table 4

Asset classification [1]

Asset	RDS-PP Code	Description
PV array (PV generator)	=MQA	Main system consisting of interconnected PV modules
PV inverter	=MSE	Converting DC current from PV into AC current
PV circuit breaker	=MSC	PV generator circuit breaker
Transformer	=MST	Transformer for power distribution
MV field distribution	=AHQ	Medium-voltage distribution
Fire protection system	=AXB	Fire protection system
Earthing/grounding system	=XFA	Grounding system
Video monitoring system	=XSB	Video monitoring system
Control and management systems	=C__	Control and management systems

In Table 4, various assets are identified along with code references and descriptions. A PV array is the main system consisting of connected PV modules serving as energy sources. PV inverters play a role in converting DC current into AC current, while a PV circuit breaker functions to cut off the circuit in case of disturbance. A transformer is necessary for power distribution, while medium-voltage distribution system (MV field distribution) manages electricity flows to consumers. To ensure safety, there is a fire protection system and a grounding system. A video monitoring system, as well as control and management systems, are involved in operational monitoring and management. An electric installation is also included for lighting and power supply.

Furthermore, the researcher describes damage priority to various component assets that have been classified previously. In the analysis, every component is rated based on three important factors: severity, occurrence (likelihood) of damage, and detection. This assessment aims to identify which components need more attention in terms of maintenance and risk management.

5. 2. Determining SOD rankings for risk assessment in IKN PLTS assets

Following the asset classification, the next crucial step in the FMEA process involves determining the Severity (S), Occurrence (O), and Detection (D) values for each identified failure mode. These values are then used to calculate the SOD ranking, which provides a preliminary assessment of the risk associated with each component. Table 5 presents the SOD ranking for the IKN PLTS assets, offering insights into their potential failure modes and their respective impacts.

Table 5

Asset damage priority

Component	Severity (*S*)	Occurrence (*O*)	Detection (*D*)	SOD Ranking
PV array	8	6	4	High
PV inverter	7	5	3	Medium-high
PV circuit breaker	5	4	6	Low
Transformer	9	3	2	High
MV field distribution	6	4	5	Low
Fire protection system	10	2	3	Very high
Earthing/grounding system	8	3	4	High
Video monitoring system	4	6	5	Low-medium
Control and management systems	7	5	4	Medium-high

In Table 5, the assessment of damage for every component is made using the SOD (severity, occurrence, detection) rating. The fire protection system stands out with the highest severity ranking of 10, highlighting the importance of ensuring consistent functionality for safety. On the other hand, the PV array and transformer also receive significant severity rankings of 8 and 9, indicating the failure of components. This can result in serious consequences. Meanwhile, other components, such as the video monitoring system, are positioned at a lower range, indicating the need for various level management in their maintenance strategy. This analysis allows the management team to estimate effective maintenance actions to protect important assets from potential damage.

5. 3. Risk analysis and priority for preventing damage to solar power plant systems in IKN

The values in the SOD column are used to determine priority preventive and repair actions for the solar power system. Table 6 presents various types of damage, main causes, and potential impact on the assets of the PLTS system. This identification aims to find out which areas are most vulnerable to damage so that preventive actions can be quickly prepared.

Table 6

Collection of damage, causes and impacts on the PLTS system

Asset	Fault type	Potential impact	Reference
PV array	Module inactivity, hotspot, shading	Decrease in total output power, risk of power loss for customers	[11]
PV inverter	DC to AC conversion failure, inverter overheating	Decrease in system efficiency, risk of local blackout	[12]
PV circuit breaker	Overheating, open/close mechanism failure	Damage to other components, increase in system downtime	[13]
Transformer	Insulation failure, overload	Overheating, potential total system failure	[14]
MV field distribution	Distribution failure, short circuit	Disturbance of power distribution, can cause blackout	[14, 15]
Fire protection system	False alarm, sensor fault	Risk of major damage to assets in case of fire detection failure	[16]
Earthing/grounding system	Unstable connection, grounding overload	Risk of electric shock and component damage	[17]
Video monitoring system	Camera offline, bad network connectivity	Disturbance in the PV RTU software communication system	Internal sources
Control and management systems	Automatic control disturbance, firmware failure	Decrease in efficiency, potential downtime on the entire system	Internal sources

To comprehensively understand the potential risks within the IKN PLTS, it is crucial to analyze the specific types of damage, their causes, and their potential impacts on the system. Table 6 provides a detailed overview of these aspects, associating each asset with potential fault types, their consequences, and relevant references for further investigation.

In Table 6, each line describes a certain asset, identification code, type of damage, and potential impact that may occur if the damage is not quickly repaired.

For example, PV module inactivity will lower power output, while transformer insulation failure will cause overheating and potential catastrophic failure throughout the system.

This section discusses the findings of the risk analysis conducted on the IKN PV system, focusing on the interpretation of the results and their implications for system reliability and maintenance. The results presented in the form of RPN and failure modes rating values highlight the criticality of certain components in the IKN PV system. The PV array, with high RPN and failure modes rating, emerged as the most vulnerable component, requiring priority attention in terms of maintenance and mitigation strategies. This vulnerability can be attributed to the array's direct exposure to environmental factors and its crucial role in energy generation.

Compared to existing studies that primarily focus on individual failure modes, this study provides a comprehensive risk assessment framework that considers the interactions between various components and their potential failures. The RPN methodology, combined with failure modes rating, offers a quantitative and comparative approach to risk assessment, allowing for prioritized maintenance scheduling and resource allocation.

However, this study acknowledges certain limitations. The accuracy of the risk assessment is highly dependent on the quality of the input data, which includes data sources and access to a deeper system. This is because the PV system project is still new and quite sensitive. so this research must continue to be carried out periodically to obtain more effective results. Future research can address these limitations by combining real-time monitoring data and advanced analytics to improve the accuracy and dynamism of risk assessment. In addition, expanding the scope of FMEA to include external factors such as weather patterns and grid stability can provide a more holistic understanding of the risks affecting IKN PLTS. Despite these limitations, this study makes a significant contribution to the field of renewable energy risk management by providing a practical and adaptable FMEA framework for IKN PLTS. The findings and recommendations presented serve as a valuable resource for optimizing maintenance strategies, improving system reliability, and supporting Indonesia's vision for a sustainable and resilient new capital city.

Furthermore, Table 7 provides an evaluation of the Risk Priority Number based on the level of severity, occurrence, and detection of the identified type of damage across various equipment in the PLTS system. The RPN value is used to determine the priority of risk mitigation activities.

The table above gives a score for each *S*, *O*, and *D* indicator and RPN values as a result of multiplication. The RPN values obtained from the FMEA table are then sorted from highest to lowest. This helps researchers identify which factors have a negative impact on the project, from greatest to least. The higher the RPN value of the risk factor analyzed, the greater the negative impact.

After determining the SOD ranking, the Risk Priority Number (RPN) is calculated for each asset. The RPN provides a quantitative measure of risk by considering the severity, occurrence, and detectability of potential failures. This allows for prioritization of maintenance efforts and resource allocation. Fig. 2 visually represents the RPN for each asset in the IKN PLTS, offering a clear overview of the risk landscape.

The picture shows failures with high RPN. From this mapping, further actions can be taken to overcome failures in the solar power generating system.

After identifying the priority from the RPN value, the next step is to determine right recommendations to take appropriate mitigation strategies or steps depending on the type of damage that occurs. Table 8 serves as a guide recommending methods to mitigate various types of damage identified in the PLTS system. These recommendations are arranged based on RPN values and related literature studies to reduce potential risks and increase system reliability in general.

Based on the RPN values and the identified failure modes, the final step in the FMEA process involves developing specific recommendations to mitigate the risks. These recommendations aim to minimize the likelihood of failure and reduce their potential impact on the IKN PLTS. Table 8 presents a comprehensive list of recommendations tailored to each asset, along with relevant references to support their implementation.

Based on the data above, a plan of recommended actions is given for various types of damage, such as regular module inspection and cleaning to reduce shading effects on the PV array, and real-time inverter temperature monitoring to prevent overheating. Each recommendation is provided with reference literature for more effective implementation, while recommendations that lack library references are expected by researchers to become effective risk mitigation means.

Table 7

Risk priority number of damage to solar power equipment

Asset	Fault type	Severity (*S*)	Occurrence (*O*)	Detection (*D*)	RPN($S \times O \times D$)
PV array	Module inactivity, hotspot, shading	8	6	4	192
Control and management systems	Automatic control disturbance, firmware failure	7	5	4	140
PV circuit breaker	Overheating, open/close mechanism failure	5	4	6	120
MV field distribution	Distribution failure, short circuit	6	4	5	120
Video monitoring system	Camera offline, bad network connectivity	4	6	5	120
PV inverter	DC to AC conversion failure, inverter overheating	7	5	3	105
Earthing/grounding system	Unstable connection, grounding overload	8	3	4	96
Fire protection system	False alarm, sensor fault	10	2	3	60
Transformer	Insulation failure, overload	9	3	2	54

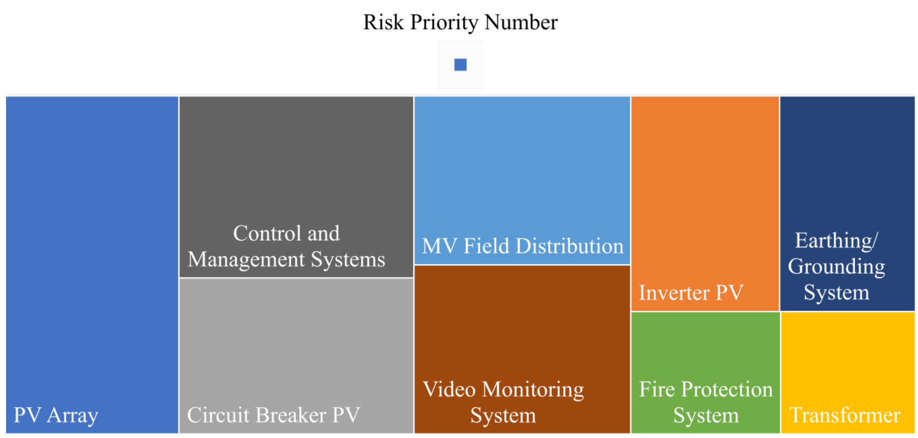

Fig. 2. Risk priority number

Table 8

Recommendations to overcome failures

Asset	RPN	Fault type	Recommendation	References
PV Array	192	Module inactivity, hotspot, shading	Regular module inspection and cleaning to reduce shading effects. Using hotspot monitoring technology	[18]
Control and management systems	140	Automatic control disturbance, firmware failure	Regular firmware updates and training of personnel operating the control system	[19]
PV circuit breaker	120	Overheating, open/close mechanism failure	Regular testing and maintenance of circuit breakers to ensure optimal performance	[20]
Video monitoring system	120	Camera offline, bad network connectivity	Replacing the existing SD card inside the PV RTU	–
MV field distribution	120	Distribution failure, short circuit	Implementing an advanced monitoring and control system to detect distribution errors	[21]
PV inverter	105	DC to AC conversion failure, inverter overheating	Implementing an effective cooling system and real-time inverter temperature monitoring	[22]
Earthing/grounding system	96	Unstable connection, grounding overload	Regular inspection and repair of the grounding connection to prevent electric shock risks	[23]
Fire protection system	60	False alarm, sensor fault	Regular testing and maintenance of the fire protection system to ensure fast response and provide automatic fire extinguishing	[24, 25]
Transformer	54	Insulation failure, overload	Regular isolation testing and installation of an overheating protection system	[26]

6. Discussion of analyzing risks for effective maintenance of renewable energy plants in the New Green Capital City of Indonesia

The research begins by outlining the key components of the IKN PLTS system, as shown in Table 4. These include PV arrays, inverters, PV circuit breakers, transformers, fire protection systems, grounding systems, video monitoring systems and control & management systems. Each of these elements is crucial to the system's overall functionality and dependability. The PV array is the major component that produces energy, but it is subject to inactive modules, hot spots and shading, all of which reduce energy production. In the same sense, a PV inverter is responsible for power conversion, but excessive heat and malfunction may hinder its proper functioning. Automatic control disturbances and firmware bugs can make control and management systems ineffective, and this can alter the operations of the entire system. Fire protection systems and grounding systems are other safety components that can be affected by sensor faults and bad connections. In-depth component classification serves as a means through which all possible threats are well evaluated and this provides a basis for the next failure mode assessment and risk prioritization.

The study identified and classified failure modes within critical components of Solar Power Plants in Indonesia's National Capital City. The analysis showed that PV arrays, with an RPN of 192, Control and Management Systems with an RPN of 140, and PV Circuit Breakers with an RPN of 120, are the most critical areas for intervention. The results show that the most dominant failure modes were environmental factors, such as shading and module failure, and technological challenges, including firmware errors and mechanical disruptions.

The high RPN value for PV arrays indicates their vulnerability to environmental conditions and the cascading effect of failures on overall energy generation. This finding underscores the need for proactive maintenance strategies like regular inspections and advanced hotspot monitoring systems (Table 7). Similarly, control and management systems require firmware updates and improved training programs to mitigate automation-related risks effectively. The continuous mapping of the risk for each component based on the severity, occurrence, and detectability confirms the strength of the FMEA methodology applied.

Unlike previous studies that focus primarily on isolated failure modes, this research integrates a comprehensive FMEA framework tailored to the specific operational context of IKN PLTS. For instance, earlier analyses [2, 3] often neglect the interplay between mechanical and environmental factors. This study bridges that gap by combining quantitative RPN values with actionable insights tailored to Indonesia's renewable energy goals. For example, unlike [4], which applies a generalized risk framework to PV-Thermal systems, this study's focus on PV-specific challenges (e.g., hotspot formation) allows for more precise mitigation strategies. The tailored recommendations, such as implementing real-time monitoring systems, demonstrate practical solutions that leverage advanced data analytics for enhanced predictive maintenance.

The solutions proposed effectively address the challenges identified in the literature review and problem statement. The key issues, such as the lack of systematic risk assessment and operational inefficiencies in PLTS, have been mitigated through:

1. A detailed classification of potential failure modes is given in Table 4.

2. Quantitative prioritization using RPN (Table 7).

3. Specific recommendations to improve system reliability (Table 8).

The findings of this study have limitations stemming from the novelty of the IKN PV project and incomplete historical data on system performance. In addition, reliance on FMEA for risk assessment may overlook risks that arise from external factors such as climate variability and grid stability. Future integration of real-time monitoring systems can address these data gaps and provide a dynamic understanding of system risks. Apart from that, the use of PV systems in IKN is still quite new. Indonesia only moved its capital in October 2024 and the development of PV has only been underway since 2023, so it still requires a lot of evaluation in collaboration with various parties to be able to analyze the risks that may occur from various sides.

Future research could significantly expand the scope of this study by incorporating machine learning techniques to enhance predictive maintenance capabilities. Additionally, expanding the risk framework to account for external factors such as extreme weather patterns and geopolitical risks would provide a more comprehensive understanding of vulnerabilities. Longitudinal studies evaluating the performance of mitigation strategies over time are also essential to refine and validate the proposed solutions. These advancements could offer scalable, adaptable solutions for renewable energy systems in similar urban contexts.

7. Conclusions

1. A comprehensive list of potential failure modes was identified across critical PLTS components (PV arrays, inverters, control systems). These failure modes were categorized according to their nature (e.g., electrical, mechanical, environmental) and potential impact on system performance.

2. Each identified failure mode was analyzed for its severity (impact on system operation), occurrence (probability of happening), and detection (likelihood of early identification). This analysis led to the calculation of Risk Priority Numbers (RPNs) for each failure mode. The research produced a risk ranking from highest to lowest, with the highest risk (RPN 192) attributed to the PV array, specifically module inactivity or disconnection, followed by shading effects. Grounding errors pose a significant risk due to potential electrical safety issues like electric shock hazards and component damage. Inactive or disconnected photovoltaic modules can lead to substantial energy loss and disrupt system stability. Furthermore, photovoltaic shading can significantly reduce electricity production due to the domino effect on the entire module string. The second highest risk (RPN 140) is associated with control and management systems, primarily due to automatic control disturbances and firmware failures. The third highest risk (RPN 120) is shared by the PV circuit breaker and video monitoring system.

3. Actionable recommendations were formulated to mitigate the identified risks. These recommendations encompass preventive maintenance strategies (e.g., cleaning schedules, regular inspections, component replacement plans), technological upgrades (e.g., advanced monitoring systems, more robust components), and best operational practices. Specific and detailed mitigation strategies for high-priority failure modes. This might include examples such as "Implementation of a real-time monitoring system to detect early signs of inverter malfunction" or "Adoption of specific technology to improve the resilience of PV arrays against specific environmental factors".

Conflict of interest

The authors declare that they have no conflict of interest in relation to this research, whether financial, personal, authorship or otherwise, that could affect the research and its results presented in this paper.

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Data availability

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Use of artificial intelligence

The author has used artificial intelligence technology within acceptable limits to maximize the vocabulary of the writing.

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