

SESSION E: THERMAL TECHNIQUE AND ENVIRONMENTAL PROTECTION

Integrated risk assessment and digital twin-based safety management in photovoltaic systems

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ARTICLE INFO

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DOI: <https://doi.org/10.46793/ET26.E01B>

PAGES: E1 – E10

ABSTRACT

The rapid expansion of photovoltaic (PV) systems has increased the importance of effective occupational health and safety management throughout the system life cycle. While photovoltaic technology is generally considered a safe and sustainable energy solution, numerous technical, environmental, organizational, and occupational hazards remain present during manufacturing, installation, operation, maintenance, and decommissioning phases. This paper presents a comprehensive literature review of risks associated with photovoltaic systems and proposes a Digital Twin-Assisted Failure Mode and Effects Analysis (DT-FMEA) framework for integrated risk assessment. The proposed approach combines traditional risk assessment principles with digital twin technology, enabling continuous monitoring, predictive diagnostics, and dynamic risk evaluation. The framework integrates technical, health-related, environmental, and social risk factors into a unified model capable of supporting predictive maintenance and proactive safety management. The results indicate that digital twins can significantly improve hazard detection capabilities, reduce risk priority levels, and enhance the overall sustainability and safety performance of photovoltaic installations. The study contributes to the development of next-generation safety management systems for renewable energy infrastructures.

KEYWORDS

Photovoltaic systems, Digital twins, Risk assessment, FMEA, Occupational safety, Predictive maintenance

1. INTRODUCTION

Photovoltaic (PV) systems have become one of the fastest-growing renewable energy technologies worldwide and are widely recognized as a cornerstone of the global energy transition. Continuous technological advancements, decreasing manufacturing costs of solar modules, and increasing international commitments to greenhouse gas emission reduction have accelerated the deployment of photovoltaic installations across industrial facilities, public infrastructure, and residential applications. Due to their capability to generate electricity without direct fossil fuel combustion, PV systems are considered a key technology for achieving sustainable energy development and reducing the environmental footprint of the energy sector [4–6].

Despite their numerous environmental and economic benefits, photovoltaic systems are not entirely free from risk. Existing studies demonstrate that a wide range of technical, occupational, environmental, and social risks may arise throughout the entire life cycle of a PV installation, including manufacturing, transportation, installation, operation, maintenance, recycling, and final decommissioning [4–6]. Among the most significant hazards are electrical risks associated with direct current systems, arc faults, fire incidents, working at heights during installation and maintenance activities, and potential exposure to hazardous substances contained in certain photovoltaic components. Furthermore, the rapidly increasing volume of damaged and end-of-life solar panels raises important concerns regarding waste management, resource recovery, and the development of sustainable recycling strategies, which are becoming critical challenges for the long-term sustainability of the solar industry [11,12].

Beyond technical and environmental considerations, growing attention is being directed toward social and organizational dimensions of sustainability. Contemporary safety and sustainability frameworks emphasize that the overall performance

of photovoltaic systems should not be evaluated solely through energy efficiency and emission reduction metrics. Equally important are factors related to occupational health and safety, working conditions, workforce training, organizational practices, and the broader social implications of global photovoltaic supply chains [7,10]. As a result, modern approaches increasingly advocate the adoption of integrated risk management strategies capable of simultaneously addressing technical reliability, worker protection, environmental stewardship, and social responsibility.

Previous research has predominantly focused on isolated categories of risk, with most studies examining technical failures, electrical hazards, environmental impacts, or occupational safety issues independently. Comparatively fewer investigations have attempted to integrate these diverse risk dimensions into a comprehensive analytical framework capable of capturing their interactions and cumulative effects on system performance and sustainability [8,13]. At the same time, recent advances in digitalization, real-time monitoring, and digital twin technologies have opened new opportunities for the development of dynamic and predictive approaches to risk management in photovoltaic systems.

Therefore, this paper aims to systematize current knowledge through a comprehensive review of the literature and to examine the evolution of risk management approaches in photovoltaic systems—from early studies focused on individual technical hazards to contemporary integrated frameworks that combine technical, occupational, environmental, and social risk factors. Particular attention is given to the potential role of digital twin technologies in supporting continuous monitoring, predictive diagnostics, and more effective safety management throughout the life cycle of photovoltaic installations.

2. DEVELOPMENT OF RESEARCH THROUGH THE LITERATURE

2.1. Initial Research on Environmental Risks (2000–2014)

Early research on photovoltaic system safety primarily focused on environmental and occupational health concerns associated with the manufacturing phase of solar technologies. One of the pioneering studies in this field was conducted by [4], who highlighted that photovoltaic cell production may involve the use of hazardous substances, including cadmium, lead, and various industrial gases. Their work emphasized the importance of adopting a life-cycle perspective when evaluating the sustainability of photovoltaic technologies, demonstrating that environmental impacts should be assessed not only during system operation but throughout the entire life cycle of photovoltaic equipment.

Building upon this foundation [5], the scope of investigation was expanded by examining occupational health risks within the photovoltaic manufacturing industry. Their study identified chemical exposure as one of the most significant hazards faced by workers during production processes and emphasized the need for stricter industrial safety procedures, improved exposure control measures, and enhanced occupational health protection programs.

Collectively, these early studies established the foundation for subsequent research by demonstrating that photovoltaic technologies, despite their environmental benefits during electricity generation, may generate important environmental and occupational risks during manufacturing and end-of-life stages. Furthermore, they contributed to the emergence of life-cycle-oriented safety assessments, which later became a central element of integrated risk management approaches in the photovoltaic sector.

2.2. Focus on Installation Safety (2017–2021)

As the deployment of photovoltaic systems expanded globally, research attention increasingly shifted toward operational and installation-related safety issues. Photovoltaic installations pose unique electrical safety challenges because solar modules continue to generate direct current when exposed to sunlight, regardless of whether the system is formally disconnected from the grid [1]. Consequently, maintenance personnel and emergency responders may remain exposed to hazardous voltages even during shutdown procedures.

Their study identified several critical electrical hazards associated with photovoltaic systems, including:

- electric shock;
- electrical arc faults;
- fires originating from direct current (DC) installations.

Among these hazards, arc faults have attracted particular attention due to their potential to initiate fires and cause severe damage to electrical equipment. Unlike conventional alternating current systems, direct current arcs are more difficult to interrupt and may persist for extended periods, increasing the likelihood of thermal damage and fire propagation.

The findings [1] significantly contributed to the understanding of photovoltaic-specific electrical hazards and highlighted the need for improved protection systems, enhanced installation practices, and specialized safety procedures for maintenance personnel. Their work also stimulated further research into fault detection technologies, electrical protection devices, and advanced monitoring systems aimed at reducing operational safety risks in photovoltaic installations.

2.3. Expansion to Social and Organizational Aspects (2022–2024)

As photovoltaic technologies became increasingly integrated into global energy systems, research attention gradually expanded beyond purely technical and operational safety concerns toward broader social, environmental, and organizational dimensions of sustainability. This shift reflects the growing recognition that the long-term success of photovoltaic systems depends not only on technical reliability but also on their impact on workers, communities, and resource management throughout the entire life cycle.

Bonilla-Alicea and Fu [10] contributed to this transition by extending the assessment of photovoltaic sustainability beyond traditional engineering considerations. Their analysis demonstrated that the sustainability performance of photovoltaic systems is influenced by several social factors, including working conditions, resource availability, and regional inequalities associated with technology deployment and access to renewable energy infrastructure. The authors emphasized that social sustainability should be considered alongside environmental and economic objectives when evaluating the overall benefits of photovoltaic technologies.

Further expanding the life-cycle perspective [6], demonstrated that risks associated with photovoltaic systems are present throughout all stages of their life cycle, from raw material extraction and manufacturing to operation, recycling, and final disposal. Particular attention was devoted to the growing challenge of photovoltaic waste management, as the increasing number of end-of-life solar panels creates significant environmental, logistical, and regulatory concerns. Their findings highlighted the importance of developing sustainable recycling strategies and circular economy practices to support the long-term viability of the solar industry.

At the same time, contemporary Health, Safety, and Environment (HSE) frameworks [9] increasingly advocate the integration of occupational health protection, environmental stewardship, ergonomic principles (Fig. 2), and organizational safety practices into a unified management system. Such approaches recognize that technical failures, environmental impacts, and human factors are closely interconnected and should be addressed through comprehensive risk management strategies rather than isolated safety measures.

Collectively, these studies marked a significant evolution in photovoltaic safety research, shifting the focus from individual hazards toward integrated life-cycle risk management approaches that simultaneously consider technical, environmental, occupational, and social dimensions of sustainability.

2.4. Contemporary Trends in Integrated and Digitalized Risk Management (2025–2026)

Recent research demonstrates a clear transition from the assessment of individual hazards toward integrated and data-driven risk management approaches. As photovoltaic systems become increasingly complex and interconnected, traditional safety management methods based on periodic inspections and static risk assessments are being supplemented by digital technologies that enable continuous monitoring and predictive decision-making.

Shafira and Abadi [8] contributed to this development through the introduction of a Health, Safety, Environment, and Ergonomics (HSEE) framework, which jointly considers technical, environmental, and human factors affecting photovoltaic system performance and safety. Their work emphasizes that effective risk management requires a holistic perspective capable of addressing interactions among engineering, occupational, and organizational dimensions.

At the same time, sustainability-related research continues to highlight the growing importance of end-of-life management of photovoltaic equipment. Studies focusing on waste management and recycling [11,12] identify the increasing volume of decommissioned solar panels as one of the major challenges facing the photovoltaic industry. These findings reinforce the need for life-cycle-oriented risk management strategies that extend beyond system operation and include recycling, resource recovery, and environmentally responsible disposal practices.

A particularly significant trend emerging in recent years is the increasing adoption of digitalization technologies within photovoltaic systems. Contemporary studies [13,15] emphasize the growing importance of digital monitoring, predictive maintenance, component health assessment, and supply chain transparency. Advanced monitoring systems enable continuous observation of operational parameters, while predictive maintenance approaches support the early detection of degradation mechanisms and potential failures before critical incidents occur.

Among these digitalization technologies, digital twins have emerged as one of the most promising solutions for future photovoltaic safety management. By creating a virtual representation of physical photovoltaic assets and continuously synchronizing operational data between physical and digital environments, digital twins provide enhanced visibility into system behavior and support real-time condition assessment. Such capabilities enable earlier identification of hazards, improved maintenance planning, and more effective risk mitigation strategies throughout the system life cycle.

Furthermore, Zafar et al. [7] demonstrated that social risks are becoming increasingly important alongside technical and environmental considerations. Issues such as workforce safety, labor conditions, supply chain responsibility, and equitable access to renewable energy technologies are now recognized as essential elements of sustainable photovoltaic development. This broader perspective is further supported by existing regulatory frameworks [14], which emphasize systematic management of waste streams, hazardous materials, and environmental responsibilities throughout the life cycle of photovoltaic equipment.

Collectively, these developments indicate that the future of photovoltaic safety management lies in integrated, data-driven approaches that combine technical reliability, occupational health and safety, environmental stewardship, and social sustainability. Digital twins, predictive analytics, and continuous monitoring technologies are expected to play a central role in enabling this transition from reactive safety management toward proactive and predictive risk management frameworks

2.5. Digital Twins in Photovoltaic Safety Management (2025–2026)

Recent developments in photovoltaic (PV) systems have increasingly focused on the application of digitalization technologies to improve operational reliability, maintenance efficiency, and occupational safety. Among these technologies, digital twins have emerged as one of the most promising approaches for the continuous monitoring and management of complex technical systems [15].

A digital twin can be defined as a virtual representation of a physical asset, process, or system that continuously exchanges data with its real-world counterpart through sensors, communication networks, and analytical models. In photovoltaic applications, digital twins enable real-time observation of operating conditions, prediction of equipment degradation, detection of abnormal operating states, and optimization of maintenance activities. Unlike conventional monitoring systems, which primarily provide descriptive information regarding system performance, digital twins allow predictive and prescriptive analyses that support proactive decision-making.

Recent studies indicate that digital twins are increasingly being used for monitoring photovoltaic module performance, inverter diagnostics, thermal behavior analysis, fault detection, and predictive maintenance planning. The integration of Internet of Things (IoT) devices, cloud computing platforms, and artificial intelligence algorithms enables the continuous acquisition and processing of operational data, providing a dynamic representation of the system throughout its life cycle [17].

From the occupational health and safety perspective, digital twins offer significant advantages. Continuous monitoring of electrical parameters, environmental conditions, and equipment status allows the early identification of hazards that may lead to worker injuries or system failures. Potential risks such as arc faults, insulation degradation, inverter overheating, abnormal current flows, and excessive thermal loading can be detected before developing into critical incidents. Consequently, maintenance interventions can be planned based on actual system conditions rather than fixed inspection intervals, reducing worker exposure to hazardous situations.

In addition to technical benefits, digital twins support integrated risk management by combining operational, environmental, and organizational information within a unified analytical framework. Such an approach aligns with contemporary sustainability principles, which require simultaneous consideration of system reliability, worker safety, environmental protection, and economic efficiency. The growing adoption of digital twins represents a transition from traditional static safety assessments toward dynamic risk management approaches based on continuous data acquisition and predictive analytics. Therefore, digital twins are increasingly recognized as an important component of future photovoltaic safety management systems.

3. DIGITAL TWIN-ASSISTED FMEA METHODOLOGY

3.1. Conceptual Approach

To overcome the limitations of traditional static risk assessment approaches, this study proposes a conceptual framework that combines Failure Mode and Effects Analysis (FMEA) with digital twin technology for the assessment of occupational, technical, environmental, and organizational risks in photovoltaic systems.

Traditional risk matrices primarily evaluate hazards based on predefined probability and consequence estimates derived from historical observations or expert judgment. Although such approaches provide a useful overview of potential hazards, they do not adequately capture the dynamic nature of modern photovoltaic installations, where operating conditions continuously change due to environmental influences, equipment aging, and varying operational loads.

The proposed methodology introduces a Digital Twin-Assisted FMEA (DT-FMEA) framework in which real-time monitoring data can support the continuous reassessment of risk factors throughout the life cycle of the photovoltaic system. The framework integrates technical system behavior, environmental conditions, maintenance information, and occupational safety indicators into a unified risk assessment model.

The conceptual architecture consists of five interconnected layers:

- Physical photovoltaic system;
- Sensor and data acquisition layer;
- Digital tin model;
- Data analytics and prediction layer;
- Risk assessment and decision-support layer.

The physical system continuously generates operational data through installed sensors measuring electrical, thermal, mechanical, and environmental parameters. These data are transferred to the digital twin environment, where the current state of the system is replicated and analyzed. Advanced analytical algorithms identify abnormal operating conditions and

estimate future degradation trends. The obtained information is subsequently incorporated into the risk assessment process to support maintenance planning and safety management decisions.

3.2. Failure Mode and Effects Analysis (FMEA)

Failure Mode and Effects Analysis was selected as the primary assessment method because it enables systematic evaluation of multiple risk categories and is widely applied in engineering safety management [18].

The method evaluates each identified hazard using three parameters:

- Severity (S),
- Occurrence (O),
- Detection (D).

Severity represents the potential impact of a failure on worker safety, system reliability, environmental protection, or organizational performance.

Occurrence reflects the likelihood that a specific hazardous event or failure mode may occur during system operation. Detection describes the ability of existing monitoring and control mechanisms to identify the failure before significant consequences occur. The overall Risk Priority Number (RPN) is calculated as:

$$RPN = S \times O \times D \quad (1)$$

Higher RPN values indicate greater risk significance and a higher priority for implementing corrective or preventive actions.

Compared with conventional probability–severity matrices, FMEA provides a more comprehensive assessment because it explicitly incorporates the capability of hazard detection. This characteristic is particularly important in photovoltaic systems, where many failures develop gradually and may remain undetected until serious consequences occur.

3.3. Integration of Digital Twins into Risk Assessment

The key contribution of the proposed methodology lies in the integration of digital twin technology into the detection component of the FMEA model. In conventional assessments, detection capability is typically estimated using expert judgment or periodic inspection records. However, such assessments are often subjective and may not accurately reflect the actual condition of the system.

Digital twins significantly improve detection capability through continuous monitoring and predictive diagnostics. By combining real-time measurements with analytical and simulation models, the digital twin can identify deviations from normal operating conditions at an early stage. Examples include:

- identification of abnormal module temperatures indicating potential hot spots;
- detection of insulation degradation through electrical parameter monitoring;
- recognition of inverter performance anomalies;
- prediction of component failures based on degradation trends;
- identification of increased arc fault probability.

As a result, the detection parameter D can be reduced, leading to lower RPN values and improved overall risk management performance.

For example, an arc fault that would traditionally be detected only during periodic inspections may be identified immediately through digital twin monitoring. Consequently, the detection rating improves, reducing the associated risk priority number and enabling earlier intervention.

3.4. Dynamic Risk Assessment Model

Unlike traditional approaches that generate a single risk estimate, digital twins support dynamic risk assessment through continuous updating of risk parameters.

In the proposed framework, risk is considered a time-dependent function influenced by operating conditions, component degradation, environmental factors, and maintenance activities. The dynamic risk model can be expressed as:

$$R(t) = f[S(t), O(t), C(t)] \quad (2)$$

where:

1. $R(t)$ represents the overall risk level at time t ;
2. $S(t)$ represents the severity of potential consequences;
3. $O(t)$ represents the probability of occurrence;
4. $D(t)$ represents the detection capability;
5. $C(t)$ represents the current condition of system components.

This approach allows risk values to evolve throughout the operational life cycle of the photovoltaic installation. Consequently, maintenance and safety decisions can be based on actual system conditions rather than fixed schedules or historical assumptions. The proposed methodology, therefore, transforms risk assessment from a static evaluation process into a continuous safety management mechanism capable of supporting predictive maintenance, improving worker protection, and enhancing the long-term sustainability of photovoltaic systems.

4. CONCEPTUAL FRAMEWORK FOR DIGITAL TWIN-BASED RISK MANAGEMENT

Given the diversity of hazards associated with photovoltaic systems and their occurrence across different stages of the system life cycle, there is a need for a comprehensive approach to risk assessment. Traditional assessments often focus on individual categories of risk, which may overlook important interactions between technical, occupational, environmental, and social factors. To address this limitation, an integrated conceptual framework was developed to systematically identify and evaluate risks throughout the entire life cycle of photovoltaic installations.

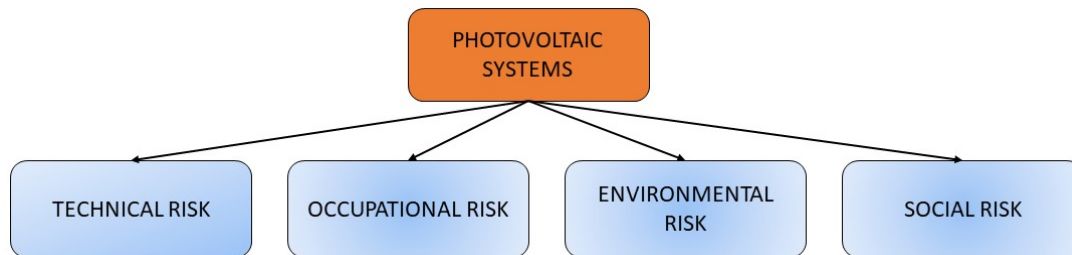


Figure 1: Interrelationship between the main risk dimensions in photovoltaic systems

Figure 1 presents an integrated conceptual framework for risk assessment in photovoltaic systems, based on the system life cycle as the fundamental analytical unit. The framework incorporates and links technical, occupational, environmental, and social risks, recognizing that these dimensions are interconnected and mutually influence the overall safety and sustainability of photovoltaic installations. Rather than acting independently, risks arising from technical failures, workplace conditions, environmental impacts, and social factors interact throughout all life-cycle phases, potentially amplifying their consequences. Therefore, effective risk assessment and management of photovoltaic systems require a holistic approach that simultaneously considers technical, occupational, environmental, and social aspects to ensure safe and sustainable system operation.

Building upon the proposed framework, which integrates physical photovoltaic assets, digital twin technology, predictive analytics, and risk management procedures into a unified safety management architecture, the present study expands the model by incorporating technical, occupational, environmental, and social risk dimensions throughout the photovoltaic system life cycle. This extension enables a more comprehensive assessment of system safety and sustainability by addressing not only operational and technical performance but also the broader impacts associated with photovoltaic installations.

The framework consists of five functional layers:

1. Physical photovoltaic infrastructure.
2. Sensor and monitoring layer.
3. Digital twin environment.
4. Predictive analytics and artificial intelligence layer.
5. Risk assessment and decision-support layer.

The physical layer includes photovoltaic modules, inverters, electrical protection devices, supporting structures, and communication infrastructure. Operational parameters such as voltage, current, temperature, irradiance, humidity, and equipment condition are continuously monitored through distributed sensor networks.

The collected information is transmitted to the digital twin environment, where a virtual representation of the photovoltaic system continuously reflects the physical installation's current operational state.

The analytical layer processes incoming data using fault-detection algorithms, degradation models, and predictive maintenance techniques. Potential failures and hazardous operating conditions are identified before critical incidents occur.

The resulting information is used to continuously update risk indicators and support maintenance planning, worker protection measures, and operational decision-making. The proposed framework transforms traditional reactive safety management into a proactive and predictive process.

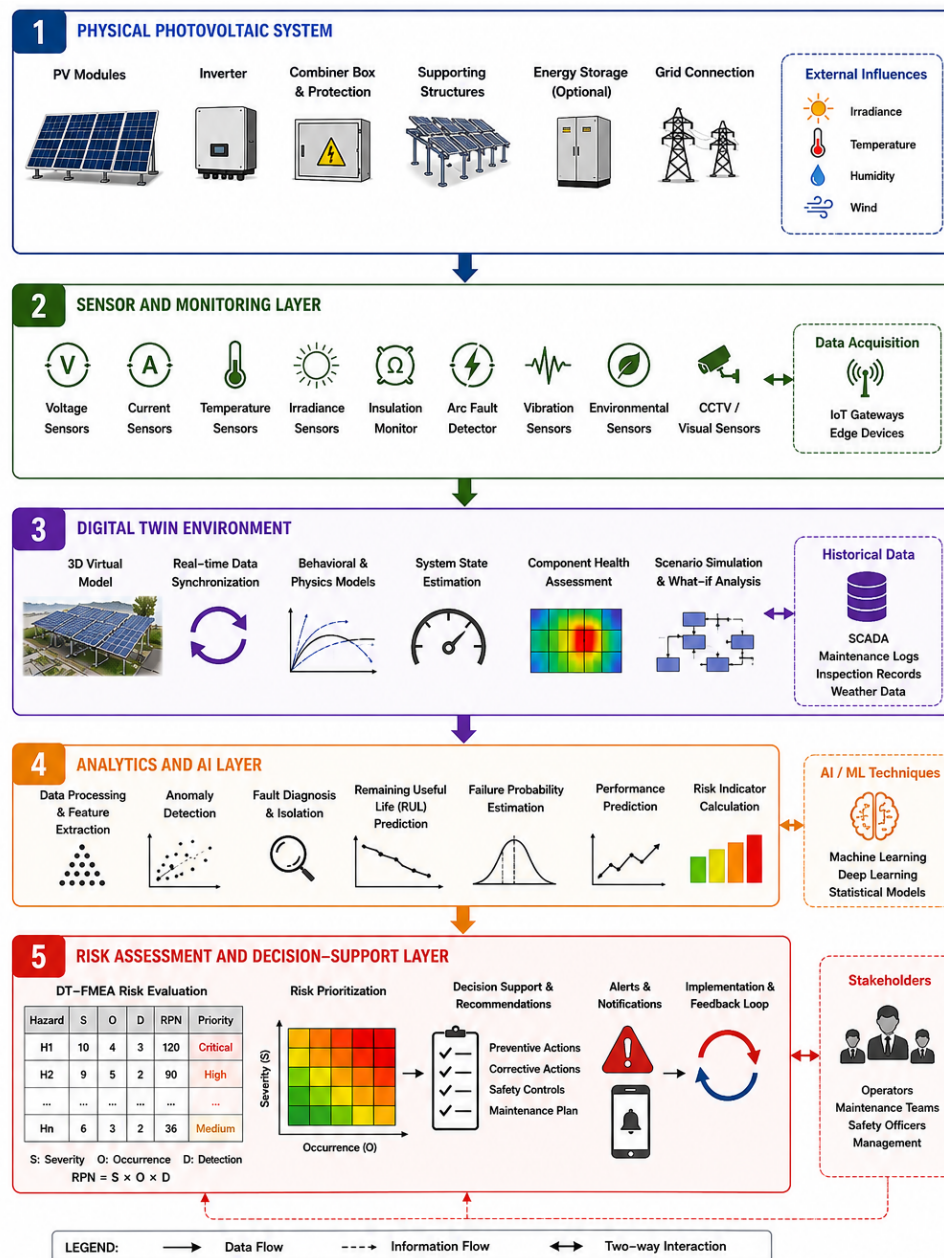


Figure 2: Digital Twin-Assisted FMEA framework for integrated risk management in photovoltaic systems

Figure 2 presents the proposed Digital Twin-Assisted FMEA framework for integrated risk management in photovoltaic systems. While this framework provides a comprehensive architecture for real-time monitoring, predictive analytics, and dynamic risk assessment, its primary focus is on operational performance and technical risk management. Building upon this foundation, the present study extends the framework by incorporating technical, occupational, environmental, and social risk dimensions across the entire life cycle of photovoltaic systems. This broader perspective enables a more holistic assessment of safety and sustainability, taking into account not only system reliability and failure prevention but also worker protection, environmental impacts, and societal considerations.

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Table 1: DT-FMEA assessment of photovoltaic system risks

Hazard	S	O	D	RPN	Priority
Electric shock	10	4	3	120	Critical
Fall from height	10	3	4	120	Critical
Arc fault	9	5	2	90	High
Chemical exposure	8	3	3	72	High
Waste management failures	8	3	3	72	High
Heat stress	6	4	3	72	Medium
Inadequate working conditions	5	3	3	60	Medium

The results in Table 1 indicate that the implementation of digital twin technology substantially enhances fault detection capabilities and reduces overall risk levels by enabling continuous monitoring and predictive diagnostics. By supporting the early identification of potential failures and hazardous conditions, digital twins contribute to the mitigation of technical, occupational, environmental, and social risks throughout the life cycle of photovoltaic systems.

Table 1 presents the DT-FMEA assessment of key risks associated with photovoltaic systems. The highest Risk Priority Number (RPN = 120) was identified for electric shock and falls from height, classifying these hazards as critical risks that require immediate preventive and control measures. Arc faults were ranked as high-priority risks (RPN = 90), reflecting their potential to cause significant technical failures and safety incidents. Chemical exposure and waste management failures also exhibited elevated risk levels (RPN = 72), highlighting the importance of environmental and occupational safety considerations throughout the system life cycle. Heat stress and inadequate working conditions were assessed as medium-priority risks, although their cumulative effects may contribute to increased accident probability and reduced workforce performance. Overall, the results demonstrate that photovoltaic systems are exposed to interconnected technical, occupational, environmental, and organizational hazards, emphasizing the need for an integrated risk management approach supported by digital twin technology.

5. DISCUSSION

The findings of this review demonstrate that contemporary photovoltaic systems operate within a complex environment characterized by the interaction of technical, occupational, environmental, and social factors. While traditional risk assessment methods remain valuable for hazard identification, their effectiveness is constrained by their static nature and reliance on periodic inspections.

The emergence of digital twin technology creates new opportunities for integrated risk management in photovoltaic systems. Through continuous data acquisition, real-time monitoring, and predictive analytics, digital twins enable the early detection of hazardous conditions and potential failures, including arc faults, inverter malfunctions, hotspot formation, insulation degradation, and abnormal operating temperatures. The integration of digital twins with the FMEA methodology further enhances risk assessment by improving failure detection capabilities and supporting proactive maintenance strategies before safety-critical situations arise.

Beyond technical performance, digital twins contribute to occupational safety by reducing the need for frequent manual inspections in hazardous environments and by providing maintenance personnel with accurate information on equipment condition before intervention. This capability helps reduce exposure to electrical hazards, falls from height, and adverse environmental conditions. At the same time, improved system monitoring and predictive maintenance support environmental protection by minimizing failures that may result in material waste, hazardous emissions, or improper end-of-life management of photovoltaic components.

The proposed DT-FMEA framework also contributes to broader sustainability objectives by increasing system reliability, reducing unplanned downtime, lowering maintenance costs, and extending asset service life. Furthermore, by supporting safer working conditions, enhancing stakeholder confidence, and promoting responsible management practices, the framework addresses important social dimensions of photovoltaic system deployment. Therefore, digital twins should be viewed not only as a technological innovation but also as a key enabler of integrated technical, occupational, environmental, and social risk management within renewable energy systems.

Future research should focus on the practical implementation and validation of digital twin-based safety management systems, as well as on the development of standardized methodologies for integrating artificial intelligence, predictive analytics, and life-cycle risk assessment into photovoltaic safety and sustainability management.

6. CONCLUSION

Photovoltaic systems represent one of the most important technologies supporting the global transition toward sustainable energy production. Despite their environmental benefits, photovoltaic installations are associated with numerous technical, occupational, environmental, and social risks that must be effectively managed throughout the system life cycle.

This study presented a comprehensive review of safety-related risks in photovoltaic systems and proposed a Digital Twin-Assisted Failure Mode and Effects Analysis (DT-FMEA) framework as a conceptual approach for integrated risk assessment. Unlike conventional static risk evaluation methods, the proposed framework enables dynamic risk assessment through continuous monitoring, predictive diagnostics, and real-time updating of safety indicators. Furthermore, the study expanded the DT-FMEA approach by introducing a life-cycle-based conceptual framework that integrates technical, occupational, environmental, and social risk dimensions into a unified assessment model.

The integration of digital twins into risk management significantly improves hazard detection capabilities and supports predictive maintenance strategies, thereby reducing the likelihood of failures and safety-related incidents. In addition to enhancing operational reliability, the framework contributes to worker protection, environmental risk mitigation, and the management of broader social impacts associated with photovoltaic system deployment.

The proposed approach represents a transition from traditional reactive safety management toward predictive, data-driven, and sustainability-oriented risk management. As photovoltaic systems continue to evolve within increasingly digitalized energy infrastructures, digital twins are expected to become a fundamental component of future safety and sustainability strategies, supporting the integrated management of technical, occupational, environmental, and social risks throughout the system life cycle.

ACKNOWLEDGEMENTS

This work has been supported by the Ministry of Science, Technological Development, and Innovation of the Republic of Serbia, through the Contract for the scientific research financing in 2026, (Contract No. 451-03-34/2026-03/200108 and 451-03-34/2026-03/200156) to build resilient infrastructure, promote inclusive and sustainable industrialization, and foster innovation, which is the ninth goal of the UN's 2030 Agenda of Sustainable Development.

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