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Risks and safety management in photovoltaic systems

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ABSTRACT

The application of solar photovoltaic systems has experienced significant growth in recent years, resulting in an increasing number of workers involved in the design, installation, operation, and maintenance of solar power plants. Although solar technology is generally considered relatively safe during operation, certain stages of its life cycle involve specific occupational health and safety (OHS) risks. This paper aims to present and systematize the key risks and protective measures in the field of solar energy through a review of scientific literature, technical reports, and relevant standards. The research methodology is based on the qualitative analysis and classification of hazards identified during different phases of solar power plant operation. The results indicate that the most common risks are associated with working at heights, exposure to direct current electrical hazards, and the influence of climatic and organizational factors. Particular emphasis is placed on the implementation of safe work procedures, the use of appropriate personal protective equipment, continuous worker training, and the introduction of safety management systems in accordance with international standards. It is concluded that effective OHS risk management requires an integrated approach combining technical, organizational, and educational measures aimed at reducing workplace injuries and improving safety in the solar industry.

KEYWORDS

Solar photovoltaic systems, Risks, Protective measures, Renewable energy sources, Occupational safety management

1. INTRODUCTION

Photovoltaic systems today represent one of the fastest-growing sources of renewable energy worldwide and play a significant role in the global energy transition. Continuous technological progress, declining costs of solar module production, and the increasing need to reduce greenhouse gas emissions have contributed to the intensive development and widespread application of solar technologies in industry, public infrastructure, and households. Owing to their ability to generate electricity without the direct combustion of fossil fuels, photovoltaic systems are widely regarded as one of the key solutions for achieving sustainable energy development and mitigating the environmental impact of the energy sector [4–6].

However, despite the numerous advantages of solar energy, recent studies indicate that the application of photovoltaic systems is not entirely risk-free. Risks associated with these systems cover a broad range of technical, health, environmental, and social aspects that arise throughout the entire life cycle of the equipment—from manufacturing and transportation, through installation and operation, to maintenance, recycling, and final disposal of panels [4–6]. Particular attention is given to electrical hazards, the potential for fire incidents, working at heights during installation and maintenance, as well as possible exposure to hazardous chemical substances present in certain components of solar modules. In addition, the growing number of decommissioned and damaged panels raises concerns regarding adequate waste management and the development of efficient recycling systems, representing a significant challenge for the long-term sustainability of the solar industry [11, 12].

In addition to technical and environmental aspects, increasing importance is also attributed to social factors related to working conditions, production organization, and global supply chains. Contemporary safety approaches emphasize that the sustainability of photovoltaic systems cannot be assessed solely through energy efficiency or emission reduction, but must also consider their impact on worker health, the quality of working conditions, and the broader social environment [7, 10].

Previous research has mostly focused on individual aspects of safety and sustainability, with the majority of studies analyzing technical failures, electrical hazards, or environmental impacts separately. A significantly smaller number of studies have attempted to integrate multiple risk dimensions into a unified analytical framework to understand their interrelationships [8, 13]. Therefore, this paper aims to systematize existing knowledge through a comprehensive literature review and present the development of risk understanding in photovoltaic systems—from earlier studies focused on isolated technical issues to contemporary integrated approaches that link technical, health, environmental, and social aspects of risk management.

2. DEVELOPMENT OF RESEARCH THROUGH THE LITERATURE

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

One of the earliest studies highlighting potential negative impacts of photovoltaic systems was the work of Fthenakis and Moskowitz [4] in 2000, which emphasized that the production of solar cells may involve hazardous materials such as cadmium, lead, and various industrial gases. The authors demonstrated that environmental impacts should not be considered only during system operation, but across the entire life cycle of the equipment.

Later, Bakhiyi et al. [5] in 2014 expanded this perspective by analyzing the impact of the photovoltaic industry on worker health. Their study highlighted the significance of chemical exposure during manufacturing processes, as well as the need for stricter industrial safety procedures.

2.2. Focus on Installation Safety (2017–2021)

White and Doherty [1] pointed out that photovoltaic systems present a specific challenge for electrical safety, as the modules remain energized even when the system is formally switched off. They identified the most significant risks as:

- electric shock,
- electrical arc (Fig. 1),
- fire caused by DC installations.

Figure 1: Arc Fault in a Solar Power System

Duroha and Macht [2] in 2023 further analyzed the risks during the installation and maintenance of solar systems. Their results showed that working at heights, manual handling of panels, and heat stress are common causes of occupational injuries in practice. Costa Lima et al. [3] demonstrated that system safety largely depends on the design itself, particularly on the layout of DC wiring and rapid shutdown systems.

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

Bonilla-Alicea and Fu [10] in 2022 expanded the research focus from purely technical issues to the social aspects of photovoltaic system implementation. Their analysis indicated that the sustainability of photovoltaic systems also includes issues such as:

- working conditions,
- resource availability,
- regional inequalities

Adekanmbi et al. [6] in 2024 demonstrated that risks associated with photovoltaic systems exist across all phases of the life cycle, from manufacturing to recycling. They particularly emphasized the issue of the growing volume of solar panel waste. At the same time, contemporary HSE approaches [9] highlight the need to integrate health protection, environmental protection, ergonomic principles (Fig. 2), and organizational safety into a unified risk management system.

Figure 2: Example of Work Activities During Photovoltaic System Installation

2.4. Contemporary Trends (2025–2026)

Recent research further shifts the focus from individual hazards toward integrated risk management. Shafira and Abadi [8] in 2025 developed an HSEE approach in which technical and human factors are considered jointly. Studies on waste management [11, 12] emphasize that solar panel recycling is becoming one of the key sustainability issues in the solar industry. Contemporary works [13, 15] highlight the importance of:

- digital monitoring of components,
- supply chain transparency,
- predictive maintenance.

Zafar et al. [7] show that social risks are increasingly becoming as important as technical factors. The regulatory framework [14] further confirms the need for systematic management of waste and hazardous materials.

3. METHODOLOGY

A systematic literature review method was applied in this study, combined with a semi-quantitative risk assessment approach. The literature was collected from relevant scientific databases and analyzed to identify key risks associated with photovoltaic systems.

3.1. Risk Assessment Method

For the assessment of identified risks, a semi-quantitative likelihood–severity matrix method was applied (Likelihood Severity Matrix). The overall risk level was determined as the product of these two parameters:

$$R = P \times S \tag{1}$$

where R is the risk level, P is the probability of occurrence, and S is the severity of the consequence.

3.2. Assessment Criteria

The parameter values were determined based on:

– frequency of occurrence in the literature
– severity of consequences
– the system life cycle phase

3.3. **Determination of probability and consequence parameters**

The values of the probability of risk occurrence (*P*) and severity of consequence (*S*) were determined based on a comparative analysis of findings from available literature. When assigning numerical values, the following were taken into account:

– the frequency of occurrence of a particular risk in the analyzed studies,
– the severity of consequences described in the literature,
– the phase of the life cycle in which the risk occurs,
– the number of authors who identify the same risk as significant.

The probability was estimated based on the relative frequency of risk occurrence in published studies, while the severity of the consequence was determined according to its potential impact on:

– human health,
– system safety,
– the environment,
– organizational sustainability.

In this way, a semi-quantitative assessment was obtained, enabling the comparison of different risk categories within a unified model.

4. CONCEPTUAL FRAMEWORK FOR RISK ASSESSMENT

To systematize the identified hazards, a conceptual framework for the integrated risk assessment of photovoltaic systems was developed, as shown in Figure 3. The proposed model is based on the system life cycle as the fundamental analytical unit and links technical, health-environmental, and social dimensions of risk into a unified assessment approach. In this way, it is possible to consider the interrelationship of different factors that determine the overall level of safety and sustainability of photovoltaic installations.

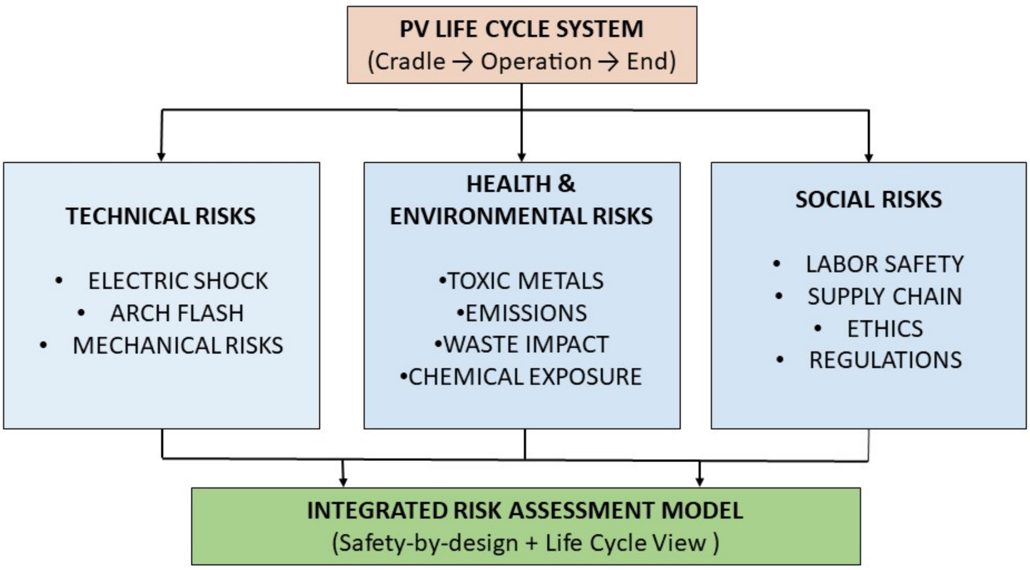

Figure 3: Conceptual framework for integrated risk assessment of photovoltaic systems

The presented model illustrates the interrelationship between technical, health-environmental, and social risks throughout the entire life cycle of a photovoltaic system. The model shows that individual risks do not act in isolation, but rather their interaction determines the overall level of system safety and sustainability.

The proposed conceptual framework shows that risk assessment in photovoltaic systems cannot be based solely on technical parameters. An electrical failure can simultaneously cause worker injury, environmental damage, and economic consequences, while inadequate working conditions can increase the likelihood of technical incidents. For this reason, it is necessary to apply an integrated risk management approach that covers all phases of the system life cycle.

5. RISK ASSESSMENT OF PHOTOVOLTAGE SYSTEMS

Based on the conceptual framework presented in Figure 3, a semi-quantitative assessment of the most significant risks in photovoltaic systems was performed. The assessment was carried out using a risk matrix based on the probability of an adverse event occurring and the severity of its consequences. This approach enables systematic risk ranking and the identification of areas where priority implementation of control measures is necessary.

Table 1: Semi-quantitative risk assessment of photovoltaic systems

Identified risk	**Risk category**	**Probability (P)**	**Consequence (S)**	**Risk value (R=P×S)**	**Risk level**	**Priority of measures**
Electric shock	Technical	3	3	9	Critical	Immediate
Electric arc	Technical	2	3	6	High	High
Fall from height	Operational	3	3	9	Critical	Immediate
Heat stress	Health-related	2	2	4	Medium	Planned
Chemical exposure	Health-environmental	2	3	6	High	High
Waste panels	Environmental	2	3	6	High	High
Inadequate working conditions	Social	2	2	4	Medium	Planned

The values of probability and consequence were determined using a three-level scale, where the value 1 indicates a low level, the value 2 a medium level, and the value 3 a high level of the assessed parameter. The total risk value was obtained as the product of probability and consequence, where a higher value indicates a higher priority for the implementation of preventive measures.

The results presented in Table 1 show that the highest level of risk in photovoltaic systems is represented by electric shock and working at height, which are classified as critical risks due to their high likelihood of occurrence and severe consequences for worker safety [1, 2]. The group of high risks includes electric arc, chemical exposure, and waste panel management, as these can cause long-term negative impacts on human health and the environment [4, 11, 12]. Social factors and heat stress are assessed as medium risks; however, their long-term neglect may indirectly increase the overall level of system safety vulnerability [7, 10].

6. DISCUSSION

The analysis of the available literature shows that risks in photovoltaic systems cannot be adequately assessed if they are considered in isolation, as there is a pronounced interdependence between technical, health, environmental, and organizational factors. Technical failures, such as electric arcs, installation damage, or component overheating, can have direct consequences for worker safety through an increased risk of electric shock, fire, or injuries during system maintenance. At the same time, such incidents can also lead to indirect consequences, including system downtime, economic losses, infrastructure damage, and negative environmental impacts due to the release of hazardous substances or the generation of hazardous waste.

Particularly important is the fact that modern safety management approaches highlight the need for integrating different disciplines in the risk assessment process. Traditional models, which were predominantly focused on the technical reliability of systems, are no longer sufficient for understanding the complexity of modern photovoltaic installations. For this reason, integrated approaches that combine engineering design, occupational health protection, environmental management, and organizational safety procedures are increasingly being applied. Such models enable the timely identification of potential hazards and the development of more effective preventive measures throughout all phases of the system life cycle.

In addition to technical and environmental aspects, social factors are also becoming increasingly important in influencing the overall sustainability of the solar industry. Working conditions during the production, installation, and maintenance of photovoltaic systems directly affect employee safety levels and system reliability during operation. Inadequate worker training, lack of protective equipment, poor work organization, or insufficiently developed regulatory mechanisms can increase the likelihood of incidents and reduce the effectiveness of protective measures. Furthermore, global supply chains and the growing production of solar equipment raise additional issues related to ethical manufacturing, sustainable resource management, and the long-term social responsibility of companies operating in the renewable energy sector.

The obtained results confirm that the sustainability of photovoltaic systems should not be viewed solely through energy efficiency and the reduction of greenhouse gas emissions, but also through the system's ability to simultaneously ensure technical reliability, worker safety, environmental protection, and socially responsible management throughout the entire life cycle.

7. CONCLUSION

Photovoltaic systems represent an important element of the modern energy transition and play a key role in reducing dependence on fossil fuels and achieving sustainable development goals. However, the results of the analyzed literature show that their widespread application simultaneously involves a complex set of interrelated technical, health, environmental, and social risks that arise throughout the entire life cycle of the system. Therefore, the safety and sustainability of photovoltaic systems cannot be viewed solely through energy efficiency or the reduction of greenhouse gas emissions, but require an integrated risk management approach. This paper developed a conceptual model for integrated risk assessment that links different categories of hazards across the stages of production, installation, operation, maintenance, and decommissioning of photovoltaic systems.

A particular contribution of this paper lies in integrating multiple risk assessment approaches into a unified analytical framework that enables a more comprehensive understanding of the interrelationships among technical, organizational, and environmental aspects of photovoltaic systems. Such an approach can serve as a basis for developing more effective safety management strategies, improving regulatory procedures, and implementing more sustainable technologies in the renewable energy sector.

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