FIRE RISK ASSESSMENT OF PHOTOVOLTAIC PANELS BASED ON THE FAILURE MODE AND EFFECTS ANALYSIS

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Abstract: An increase in the use of alternative power sources results from the transition to a green economy and the reduction of greenhouse gas emissions. Their deployment contributes to increasing energy self-sufficiency and independence from other countries. Despite the highly positive effects associated with the operation of alternative power sources, it is necessary to pay appropriate attention to providing their operational safety. Using the Failure Mode and Effects Analysis method (FMEA), this paper assesses the causes and effects as well as estimates the Risk Priority Number of photovoltaic system failures possibly resulting in fire. The paper assesses the causes of fire in the manufacturing, transportation, installation and operation phases. The Failure Mode and Effects Analysis method allowed for estimating the Risk Priority Number, with the highest being estimated for six causes, including inverter failures, malfunctioning lightning protection and fuse box failures. In total, 20 different causes were assessed, of which more than 50% can be considered acceptable.

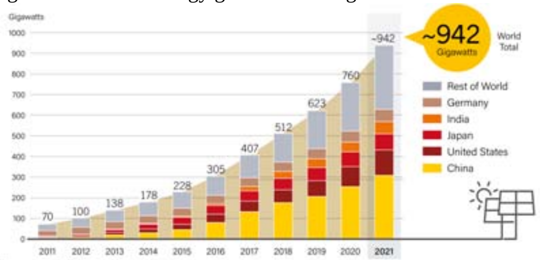
Keywords: Failure Mode and Effects Analysis (FMEA), fire, photovoltaic panels, risk, risk assessment.

1 Introduction and analysis of the current situation

The current security situation in the context of the military conflict in Ukraine, which has triggered an energy crisis accompanied by unacceptable increase in energy price and worsening climate change are the main reasons for the development of renewable energy sources. In the context of these circumstances, there is a growing demand for self-sufficiency of entities through autonomous systems of electricity provision, mainly in the form of photovoltaic power plants.

This is evidenced by the sharp increase in electricity generation through photovoltaics. In 2019, the total installed capacity of photovoltaic power generation worldwide was 623 GW. In 2021, the cumulative global capacity already exceeded 942 GW. In that year, the newly installed capacity was estimated at 175 GW, 36 GW more than in 2020 [1]. Figure 1 shows the countries with the largest cumulative photovoltaic power generation capacity in the world.

Fig.1. World solar energy generation using PV



Source [1]

Resulting of the increase in the installation of photovoltaic (PV) power plants, it is advisable to pay attention to the safety of their operation, particularly to fire safety. Failure of the functionality of PV power plants operation can cause a fire, which, by its destructive effects, can cause damage to the structures or their complete damage. Analyses of the causes of fire and failures have shown that PV systems are often installed without proper consideration of the fire spreading caused by the presence of modules, cables and electrical panels on the roof. PV modules are usually installed without considering the fire performance of the roof, especially in industrial and large warehouse facilities [2]. This leads to a violation of the fire requirements for such facilities or the systems not being included in the requirements.

Intentional and unintentional faults leading to PV system failure can occur during all stages of the PV system life cycle. The design and installation phases of a PV system focus on efficiency, reliability, and obtaining the highest possible amount of solar energy that can be converted into electricity, which may be the reason why the designers of such systems do not sufficiently consider the risk of fire, similarly to the companies installing PV equipment [3]. The existence of PV power systems on buildings can increase or contribute to the already existing fire risk level since the PV power system components can affect the fire spreading outside or inside the building, interfere with smoke and ventilation systems, produce unwanted products of fire, obstruct firefighting, or even mean an electrical shock hazard to firefighters due to energized objects [2, 3, 4].

The flammability characteristics of the components that make up a PV system depend on two factors, namely the materials used and the way they are operated and installed. In addition, various materials and technical measures are implemented to the support structures of the PV systems themselves, depending on the manufacturing and installation companies. Research has been conducted on how the gap between the PV system supporting structure and roof affects flame spreading and fire resistance ratings of roofs and surfaces [5, 6, 7].

Based on the research conducted [3-7], opinions and discussions, standard development processes have been introduced within the professional community, resulting in the IEC TC 82 "Solar Photovoltaic Energy Systems" [8] and CENELEC TC 82 "Solar Photovoltaic Energy Systems" [9] guidelines at the international level.

The Italian Fire Department, for example, based on the above-stated standards has developed and implemented regulations focused on PV modules and rooftop connectors that include procedures for categorization when installing a PV system. These measures contain amendments to some Italian national technical fire response standards that have been developed in the past for products other than PV modules (e.g. wall panels) [4]. Similarly, Germany has also developed standards for fire and technical assistance and fire protection measures in electrical systems [10, 11]. The Czech Republic is currently updating regulations and standards for a more comprehensive approach to PV power plant installations and fire protection.

It follows from the above-stated facts that documentation governing the requirements for the installation and operation of PV systems on buildings represents a crucial basis for effective fire prevention. This should be based on the identification, analysis and risk assessment of PV systems carried out. It is preferable to choose quantitative or semi-quantitative methods providing higher accuracy within the context of the risk management application.

When selecting an appropriate method for PV system risk assessment, it is necessary to define the availability of input data, the experience and knowledge of the assessors with the method, and the output requirements. There are different methods and techniques for risk identification depending on the input data requirements, the experience of the assessors, the complexity of the assessment process, etc. There is no single “best or universal method” for risk identification. Methods should be used in an appropriate combination [12], or the one that best meets the input requirements should be chosen. Risk management should be used to identify the causes, and methods and techniques such as Checklist, Hazard Operation Process (HAZOP), Event Tree Analysis (ETA) and Failure Mode and Effects Analysis (FMEA), can be used among others [12, 13].

It was found, based on research of the available scientific literature [2-7] in the field of PV risk assessment, that the most commonly used are experiments, based on which conclusions, comparisons or FMEAs are made. A comparison was used according to selected criteria - input data and the complexity of the process to select the appropriate PV risk assessment method. The comparison of the risk management methods and techniques widely used is presented in Table 1.

Tab. 1. Comparison of selected risk assessment methods and techniques

Name of method	Information intensity	Probability estimate	Risk level	Result of analysis
Checklist	High (Knowledge of conditions and measures is needed)	No	No	Qualitative
Hazard and Operability Study – HAZOP	High (It is a multidisciplinary technique)	No	No	Qualitative
Event Tree Analysis – ETA	High	No	No	Qualitative, quantitative in the case of a large number of input values
Failure Mode and Effects Analysis – FMEA	Medium	Yes	Yes	Quantitative

Source: author's own work [12-17].

The Checklist technique is used in the case of carrying out a systematic check of predetermined conditions and measures. This method is useful in an area in which the assessment team has deep experience, particularly for activities of a standard or routine character. In contrast, the HAZOP technique procedure is based on a probabilistic assessment of threats and the resulting risks. ETA technique is used for system reliability analysis and risk quantification since it illustrates the logic of combining probabilities and effects of sequences of events in a graphical representation. The analysis of failure modes and their effects, which allows the search for impacts and causes based on systematic and structured equipment failures, is solely enabled using the FMEA method [12-17].

The comparison results show that the ETA technique is the most demanding for input data, in case of a large number of input values, a quantitative result is needed to be obtained. The same is true for the HAZOP technique, which requires teamwork as it is a method used across the spectrum of experts. In the case of the Checklist, both a large amount of data and a high level of knowledge of the process are required, resulting in a qualitative result.

Considering the selection conditions set and the comparison of methods performed, the FMEA method was selected as the most appropriate method for risk assessment of PV systems. The application of the FMEA method is also suitable due to the research already conducted into PV system failures [18].

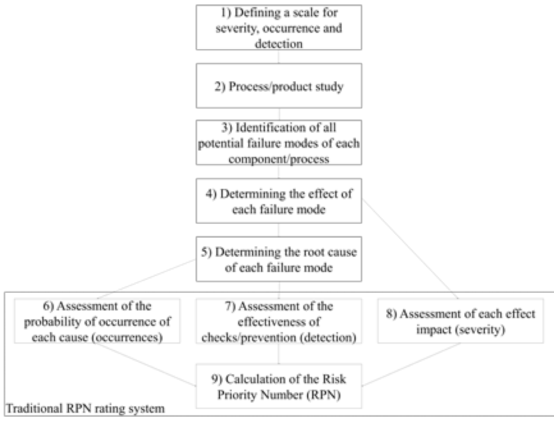
The aim of the paper is to identify the causes and effects of failures that can lead to fire hazards and to estimate the risk to the PV systems in operation using the FMEA method. The paper provides an opportunity to obtain relevant data for subsequent development and updating of fire safety regulations in the Czech Republic. A general model of the PV system operation was chosen for the purposes of the research described in the article.

2 Data and methods used

There is no publicly accessible database for collecting information on failures, only partial or outdated information is available. Companies operating and maintaining PV power plants do not publish failure data. Results on identified failures were drawn from publicly published scientific research results or research published between 2010 and 2015 [18, 21-23] and for these reasons, the background information was based on publications available in 2000 [24], 2008 [25], 2010 [19], 2011 [20], 2012 [21, 22], 2014 [23] and 2015 [18].

Failure mode and effects analysis (FMEA) is an inductive and conservative approach to system reliability analysis. A system is a complex combination of components and sub-components where technical and disciplinary interfaces are involved in their interactions. FMEA carries out an individual analysis of the sub-components of each system with the aim of identifying the different failure modes affecting each component with the causes and effects for the component itself and the whole system [18]. The traditional FMEA process is described in Figure 2.

Fig. 2. Traditional FMEA process



Source: modified by the author [17, 18]

The FMEA analysis must be carried out in steps according to the above-listed scheme, as each step builds on the previous one. An overview of the 9 steps in the FMEA process follows:

1) Defining a scale for severity, occurrence and detection - the scale was set as a scale from 1 to 10 (see Table 2), i.e. according to the established scale based on ISO 12132:2017 standard;
2) Process/product study - familiarization with available sources of information on PV system failure modes;
3) Identification of all potential failure modes of each component/process - identification of existing background materials and documentation/data on all possible failure modes, subsequently, the individual items were combined, as there are also several types of failures on individual parts of the PV system;
4) Determining the effect of each failure mode - identifying the individual impacts of failures on the end product (power generated) or on the following steps in the process or fire;
5) Determining the root cause of each failure mode - identifying the possible causes, which in this case were multiple;
6) Assessment of the probability of occurrence of each cause (occurrences) - the assessment was made on a scale from 1 to 10 (see Table 2), i.e. according to the established scale based on ISO 12132:2017 standard;
7) Assessment of the effectiveness of checks/prevention (detection) - this assesses the probability of a failure detection before it occurs;
8) Assessment of each effect impact (severity) - determined based on the severity of the effects of failures;
9) Calculation of the Risk Priority Number (RPN) - this is a product of three input factors: severity, occurrence and detection, which have been defined based on points 6 to 8 above. Subsequently, the failures with the priority given, i.e., the highest RPN, are chosen and a measure is proposed for them [16, 17, 18, 26-29].

Tab. 2. A rating scale for severity, occurrence and detection criteria

Severity	Occurrence	Detection	Assessment
Less severe	Very low	Very high	1
Not severe	Low	High	2, 3
Average	Medium	Medium	4, 5, 6
High	High	Low	7, 8
Very high	Very high	Very low	9, 10

Source: modified by the author [26]

3 Results and Discussion

Based on data obtained from professional sources [18-25], individual parts of the FMEA table (see Table 3) were elaborated using a qualified estimate with the primary focus on a technical failure, fire safety and personal safety.

Tab. 3. Analysis of failure modes and effects

No.	Potential failure	Possible causes	Possible failure effects	S	O	D	RPN
1	Loss of electrical functionality	Electric arc, exposed contacts	Fire, reduced operator safety, zero power generation	9	3	5	135
2	Electrical functionality Interference	PV panel ageing, overshading, PV panel pollution	Damage to PV panels, reduced power generation	7	2	7	98
3	Exposed contacts in modules	Disconnection of panels, incorrect installation, corrosion	Fire, zero power generation	9	1	5	45
4	Electric arc	Damaged insulation, lightning, damage by animals	Fire, damage to modules, zero power generation	9	1	3	27
5	Faulty contact	Material defect, ageing, oxidation	Reduced or zero power generation	7	1	7	49
6	Short circuit	Material defect, mechanical damage, electrical surge	Fire, reduced operator safety, overcurrent, reduced power generation	7	1	7	49
7	Diode damage	Material defect	Fire, reduced operator safety, reduced power generation, PV panel damage	5	1	7	35
8	Changing PV panel parameters	Material defect, ageing	Overcurrent, reduced power generation	4	1	7	28
9	Connectors opening	Vandalism, wind, failure to follow installation instructions	Zero power generation	9	1	3	27
10	Airtightness loss	Manufacturing defect, damage, snow load, lightning	PV panel damage, reduced or zero power generation	3	3	7	63
11	Loss of PV power plant configuration	Incorrect installation, damage	Reduced operator safety, PV panel damage, reduced power generation	7	4	1	28
12	Damage to supporting PV panel structure	Incorrect installation, material defects, weather effects	Unstable structure, damage/destruction of PV panels	6	4	3	72
13	Malfunctioning lightning protection	Incorrect installation, damage, corrosion	Reduced operator safety, module damage, reduced power generation	8	4	7	224
14	Tear and wear of PV panels	Material ageing, damage by animals, vandalism	Fire, zero power generation, reduced operator safety	9	1	3	27
15	Fuse box	Misconfiguration, design defect, improper maintenance	Fire, electric arc, reduced operator safety	9	1	8	72
16	Disconnection of the PV power plant	Misconfiguration, design defect, improper maintenance	Fire, reduced operator safety, zero power generation	9	1	5	45
17	Circuit breaker	Defective switch, improper maintenance, design defect	Fire, reduced operator safety, zero power generation	9	1	7	63
18	Inverter	Contact failure, vandalism	Reduced or zero power generation	9	7	4	252
19	Transformer	Damage to insulation / structural parts, switch failure, ageing, improper maintenance	Fire, reduced operator safety, reduced or zero power generation	8	1	2	16
20	Protective relay	Incorrect setting, improper maintenance, ageing	Fire, reduced operator safety, overcurrent, reduced energy generation	8	1	4	32

Source: author's own work [18, 21, 23, 27]

The highest values of RPN were indicated by inverter failures and malfunctioning lightning protection, which result in, among other things, two primary failures, namely zero or reduced power generation. RPN values in the range of 98 - 50 were indicated for the circuit breaker or fuse box, as well as for the supporting PV panel structure or risks associated with the airtightness loss. Other failures have an RPN below 50, where, despite the high severity of the failure, the risk factor is not high due to, for example, a low occurrence probability or a high detection rate.

Based on the analysis performed, the inverter and malfunctioning lightning protection demonstrate the highest RPN which corresponds with the available scientific sources [18, 21]. In the case of the inverter, it is up for discussion whether this happens directly due to vandalism or possible damage within faulty connectors or contacts as reported by Köntges et al. [23] or Rieder [24]. On the other hand, for malfunctioning lightning protection, the author agrees with the results of other research teams [18, 21, 23], adding that in this case, the risk of fire is quite likely and the possible causes are influenced by both human factors and weather conditions.

The fuse box reached the fifth highest risk along with damage to the supporting PV panel structure. According to the results of the studies [18, 21], the level of risk was not rated at a similar level to the author of this paper. The justification for the higher rating was identified by the author based on the higher RPN for the inverter (faulty contacts) resulting in the impact on the fuse box [23, 24], and thus the effects in the form of fire prove to have higher probability levels.

A higher level of risk was also detected for the structural part of the PV system, more precisely the supporting structure of the PV panels, although neither Colli [18] nor Golnas [21] shares a similar view, for example, because of the lower probability and higher detection rate. From the author's point of view, the factor of damage to the PV panel structure cannot be omitted in the assessment. This is primarily because of the potential damage to the roof structure leading to roof collapse and also from the perspective of fire spreading. It has been proven, according to several experiments conducted on flammability and fire spreading under PV panels, that the height of the gap between the roof and the PV panel affects the heat and flame spreading [4, 30-33]. This is the reason for the higher value of the estimated risk.

4 Conclusions

The article dealt with the analysis of possible failures in PV systems that can have an impact both on the operation and the production of electricity, as well as on fire safety or the health of the operator of this equipment. In addition to the positive benefits of PV power plant operation, it is necessary to focus on the dangers arising from its operation or lack of maintenance. A key operational risk is a fire, which affects both the PV system and the building on which it is installed. The safe operation of PV systems has to be based on regulatory legislative acts and other fire protection regulations, which are not, however, sufficiently developed in the Czech Republic.

The article, therefore, focused on risk assessment, in particular the causes that can trigger a fire. The possible individual failures were described within the article and their level of risk was assessed with respect to their severity, occurrence and detection. Each failure was analysed based on the three above-mentioned factors and rated on a scale of 1 to 10. The Risk Priority Number RPN was subsequently calculated and the failures with the highest RPN were discussed.

It is essential, regarding the results of the risk assessment, that safety features and systems for detecting fire occurrence were taken into account in the design and manufacturing phases of the PV system. Load testing or the use of modelling tools to test the resilience of individual system components should be implemented as part of the PV system test operation. The PV system operator should regularly monitor and assess the frequency of individual failures and their impact on power generation.

Correct identification of failures and root causes (those with a high occurrence or high severity) can help in decision-making already during the design, construction and subsequent operation phases. It has been proven that the inverter represents the most vulnerable component of a PV system. Manufacturers will likely improve the functionality of this component and the others with regard to the permanent development and improvement in safety and reliability. This is indicated by Golnas' findings published in his 2013 study [21].

The issue of gaps between the roof structure and the PV panels needs to be added/incorporated into the national standards, as it has not been addressed yet. Determining a minimum gap height shall reduce the spread of heat and flame between individual components. This has been proven by several studies [4, 30-33]. Another recommendation is to deal with the roof surfaces on which the PV systems are located, due to their degree of flammability, which for the time being is only addressed by recommendation and is not an obligation during installation.

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