Fault tree analysis of fires on rooftops with photovoltaic systems

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Fault Tree Analysis of Fires on Rooftops with Photovoltaic Systems

Highlights

- Qualitative and quantitative fault tree analysis of fire related to PV systems
- An annual fire incident frequency of 0.0293 fires per MW is calculated
- Poor installation practice tends to be a general issue related to many components
- Increased focus on consequence mitigation might be an effective risk reduction
- Post-incident report questions suggested for use by national fire and rescue services

Abstract

A fault tree analysis of fires related to photovoltaic (PV) systems was made with a focus of understanding the failure rate of the electric components. The failure rate of different components of these systems was calculated from data obtained from reports, research studies, and fire incident statistics of four countries. The results explain the significant causes of fire on the component level and various failure patterns resulting in PV-related fires. The qualitative analysis identified seven major events that led to incidents caused by a PV-related ignition source, with electrical arcing being the main cause of fires. This finding is highly related to the imprudent installation practices due to negligence and low awareness of the fire risk associated with PV systems by installers. The quantitative results show that 33% of the PV fire incidents are due to unknown or unrelated ignition sources, indicating that great focus should be given to mitigate the consequences caused by PV-related fires. The PV module, isolator, inverter, and connector are the major PV system components that are highly responsible for the ignition of PV-related fires, with the connector being the prime contributor in 17% of the PV-related fires. Finally, the quantitative analysis established an annual fire incident frequency of 0.0293 fires per MW. The results enable estimation of the number of fire incidents linked to the installed PV capacity, and the fault tree analyses highlight where improvements are most critical. Based on the results of the analyses, two questions are suggested for implementation in the post-incident reports of the national fire and rescue services.

Keywords: Fault tree analysis, Frequency analysis, PV fire safety, Rooftop photovoltaic installations, Photovoltaic installations, PV system failure rate

1. Introduction

Humans have utilised solar energy in many ways throughout history. In modern times, numerous ways to harness energy from the sun have been developed, and the method in which solar radiation is converted directly to electricity is becoming the most common with an increase in the global capacity from 40 GW in 2010 to 766 GW in 2020 [1-3]. Since 2010, the historical growth of the global PV power capacity has exceeded the projections from the International Energy Agency, and it is estimated that global solar power capacity will surpass one terawatt in 2022 [4-6]. The energy produced by a photovoltaic (PV) system is direct current (DC) that can be converted into alternating current (AC) by using an inverter [7]. While PV systems can be applied in any space, this research focuses on systems installed on buildings, i.e., rooftop PV systems. The PV systems consist of PV modules with an inverter and other support hardware (electrical and mechanical). The electricity generated from the PV system has become very significant in the previous decade, thus offering the prospect for the sustainable growth of electric power on a large scale [8,9].

The number of PV system installations is exponentially increasing due to the growing concern for greenhouse gas emissions, significant price drops, and government incentives for PV installations [10,11]. In urban areas, the combination of green roofs and rooftop PV systems contributes to sustainable building development [12]. The integration of these two green technologies on the building roof helps in enhancing the effectiveness of the PV system [12]. Research proves that the evapotranspiration cooling process from green roofs helps cool the ambient temperature around the modules [12], thus allowing PV modules to operate at optimal temperatures [13]. The research led by Irga shows that integration of PV system on the green roof generates a daily output that is 13% greater than for conventional roofs, and that this also improves the system efficiency by 3.6% [14].

Nevertheless, PV systems possess potential risks as all new technologies [15]. It has been observed that the fire risk increases with an increasing number of PV systems installed on buildings, either with or without the integration of green roofs [16]. This is evident from several fire incidents involving PV systems in Europe and North America [15]. In 2012, more than 600 fires involving PV systems occurred in Italy alone [16]. More recent data from the Netherlands revealed 29 PV-related fires occurred in 2018 and 2019, whereas 37 fires occurred in the first ten months of 2020 [17]. Four comprehensive reports by Pester and Woodman [18], Coonick et al. [19], Sepanski et al. [20], and Grant [21] have been written on the topic of fire safety and PV installations. Three of the reports cover national cases voluntarily reported in respectively the UK and Germany, whereas the later focus on firefighter safety. To understand the fire-related risk of roof-mounted PV systems, the reports by Coonick et al. [19] and Sepanski et al. [20] are the most relevant, as both reports contain data regarding the occurrence, consequence, and cause (when possible) of national PV related fires. In their conclusions, both reports state a series of recommendations based on the experience gained from examining the historical events. However, none of the reports include a general analysis of the underlying causes of the fires nor a quantitative overview of the consequences.

For building applied PV systems (BAPV), the main fire safety concerns can be separated into two underlying causes: (i) an increased probability of ignition due to the large DC system, and (ii) a changed fire dynamics scenario due to the enclosed space between the roof construction and the PV system [22,23]. A majority of the literature on PV-related fires focuses on fault detection, fire behaviour analysis, and the safety of installers and first responders [21,22,24-28]. In a recent study, Wu et al. [29] presented a review on PV fire prevention techniques in which it was concluded that fault diagnosis and configuration of PV panels is key to fire prevention in large-scale PV systems. Currently, there is no model that can predict the number of fire incidents due to BAPV systems.

From a fire safety science perspective, there is a significant difference between a potential source of ignition and an actual fire. An open roof construction without a BAPV system is typically designed in accordance with national standards such as UL 790 [30] or EN 13501-5 [31], which are developed to ensure that fire does not propagate upon the roof construction and thus, the building envelope of the property. Open roof constructions are designed to withstand ignition from an electric failure such as a DC arcing caused by an electric malfunction in a PV system.

However, the introduction of the PV module as a physical object installed above an ignition source modify the fire dynamic system and cause a significant increase of the heat flux towards the roof construction near the ignition source, as shown by Kristensen et al. [23] and subsequently by Ju et al. [32] and Tang et al. [33] who elaborated the experimental setup and analysis. Their findings were verified in a series of large-scale experiments, where a small initial fire propagated below four PV arrays, each consisting of six modules installed in an east/west orientated mounting system [34]. In those experiments, the fire did not propagate outside the arrays, as the flame spread was facilitated by the additional heat flux caused by the deflection of the flames below the PV modules, which is in line with observations from fire incidents. Finally, the influence of the gap distance between the roof construction and a horizontal PV module was addressed by Kristensen et al. [22] in a series of parametric experiments where they identified the existence of a critical gap height, which caused a rapid acceleration of the flame spread upon acrylic plastic (PMMA).

It is accepted that the PV system increases the fire load on the roof construction due to the vast amount of cables, but the PV modules do not constitute a significant fire load as only around 10% of modules are combustible polymers, whereas the remaining mass are mainly aluminium and glass [35,36]. Most of the combustible material is ethyl vinyl acetate (EVA), which is used to encapsulate the PV cells, whereas the two highly thermally stable fluoropolymers Tedlar® and Kynar® are among the most used products for back sheets [35,36]. Cancelliere and Liciotti tested the back sheets of four PV modules and if the calibration of the flame spread apparatus used in the Italian UNI 9173 is similar to the calibration in ASTM E1321 [37], they found that no flame spread was possible with an incident heat flux below 20 kW/m^2 [25]. That corresponds well with the findings by Kristensen, Jomaas and various co-authors [22,23], where it is concluded that the combustible back sheet of a PV module does not represent a significant fire load. The limited duration of the increased heat flux from the burning back sheet membrane is insignificant [23] and compared to a non-combustible panel, it did not increase the flame spread rate of the fire upon a subjacent fuel. At the same time, it is significantly higher than the critical heat fluxes of 6 kW/m^2 to 8 kW/m^2 determined for two EN 13501-5 compliant roofing membranes by Jacobs (B_{ROOF}(t4)) [38] and Kristensen and Jomaas (B_{ROOF}(t2)) [34]. Finally, in the large-scale experiments by Kristensen and Jomaas [34], it was concluded that the flame spread upon the subjacent roof was a result of the changed fire dynamics, and not a result of the limited fire load introduced by the PV system.

As such, the PV system itself might not represent a significant fire load to the roof construction. However, due to the semi-enclosure between the inclined PV modules and the existing roof construction, a fire can propagate on the building envelope, leading to a breach of compartmentation and, thus, a breach of fundamental fire safety principles. The existence of re-radiation from the deflected flame below an inclined surface [23,32,33], combined with the fact that the fire propagated below all of the PV arrays in the large scale experiments [34] should raise a red flag. It can only be defined as a critical issue, when a BAPV system installed on a roof construction compliant with the current European standards, cause a violation to the pre-defined acceptable level of fire safety, as the consequences might be significantly worsened due to the modified fire dynamics. The ASKO fire in Norway is a very good state-of-the-art example of the fire dynamics issue, as a fire within one compartment broke through the roof, whereupon it probably propagated along a PV-equipped roof and into another compartment [39].

Whereas understanding the PV system as a potential ignition source is a well-studied field of research, the understanding of the modified fire dynamics is an underdeveloped field. However, the fire-related risk of building applied PV systems is the product of the ignition probability times the consequence in case of ignition. It cannot be questioned that a reduced probability of ignition will cause a reduced risk, but an increased focus on mitigating the consequences in case of ignition could have a significantly larger influence on the risk. The purpose of the analysis is to obtain an understanding of the underlying causes of the PV-related fires in the four available data sets, as it might clarify whether a reduction in the probability or mitigation of the consequences would lead to the largest reduction of the risk related to BAPV systems.

A fire-related risk analysis would be ideal to obtain a full understanding of how the introduction of a PV systems into the built environment might affect the overall safety of the users, the property hosting the PV system, as well as a sustainable development of the photovoltaic marked. However, quantitative data with respect to the consequences of the PV-related fires is even more sparse than the data used to conduct the fault tree analysis of the PV system as potential source of ignition. Based on the current data available, an analysis of the consequences will have to be qualitative which would fit well with the quantitative analysis failure frequency. Furthermore, a qualitative consequence analysis would, most likely, only obtain the severe scenarios causing attention from the media and thus, the result of such analysis might be distorted and non-representative of the actual risk.

The interest in fire safety tends to be retro-active, as society have no interest in slowing down the penetration of new technologies into the marked by questioning the inherent consequences. As such, no quantitative database will exist before the existence of a potential risk is accepted by society, which might cause a significant issue due to the exponential growth of the photovoltaic technology. Of course, it is the nature of insurance companies to question the introduction of any new technology, but the behaviour by major stakeholders such as Walmart [40] highlight the potential pitfalls. This type of pitfall might have severe consequences for the society and be crucial for the implementation of PV systems into the built environment.

Despite the limited amount of research, as well as quantitative and qualitative data, that describes the fire-related consequences caused by the introduction of PV-systems into the built environment, the potential breach of fundamental fire safety strategies should raise a red flag. At best, a lack of understanding the potential consequences will, most likely, result in a slowdown of the technology as future incidents is analysed and statistical data are obtained. Neither the manufactures, property owners, society nor the environment have interest in such slowdown, which is why this analysis is still argued to be very relevant.

This study focuses on developing a model that can predict the quantitative frequency of fire incidents caused by BAPV. Besides that, a qualitative and quantitative analysis of the PV system components was conducted to understand the cause of the incidents. This was achieved through a fault tree failure analysis, which is an effective and prospective tool to analyse the safety and reliability of a system [41,42]. As such, the method has the potential to identify fault linkages in the system, highlight failure patterns before they arise, compare several designs for safety prioritisation, help authorities evaluate overall hazards, and take decisions to avoid critical failures [43]. By quantifying the fire-related failure modes introduced by PV systems in the built environment, the aim is to enable industry stakeholders, such as the regulators, designers, manufacturers, installers, and users to understand the underlying causes, whereupon they can take appropriate preventive measures to avoid loss of life and/or property. As such, this study will be a starting point for a more comprehensive PV fire risk study in the future. As the analysis is based on publicly available data from Australia, Germany, Italy, the UK and the USA, it is crucial to emphasise that it does not address the frequency of electric malfunctions in the PV system, but only the cases where an ignition has caused a fire and, thus, received attention from the fire and rescue services, property owners or installers of the system.

2. Methodology

The fault tree analysis was employed to assist in establishing potential root causes of PV-related fires on rooftops. Both qualitative and quantitative fault tree analyses were carried out with PV-related fires as the top event. Figure 1 illustrates the stages of this work. In the first stage, a comprehensive literature review was conducted by initially finding related publications from publicly available resources such as research papers, reports on PV fire investigations, and open-source data from various countries. No time boundary was applied during the search, as the result of the quantitative analysis in Stage 3 would be more comprehensive if more data were collected. It was observed that the publicly available data related to the study were from accidents that occurred between 2008 and 2018. All valuable information regarding PV-related fires was assessed, extracted, and then used in Stage 2 and Stage 3. In Stage 2, the qualitative fault tree approach helps in recognising a variety of probable reasons for the top event to occur by identifying the major, intermediate, and basic events. All the events were connected with the top event using the logic gates.

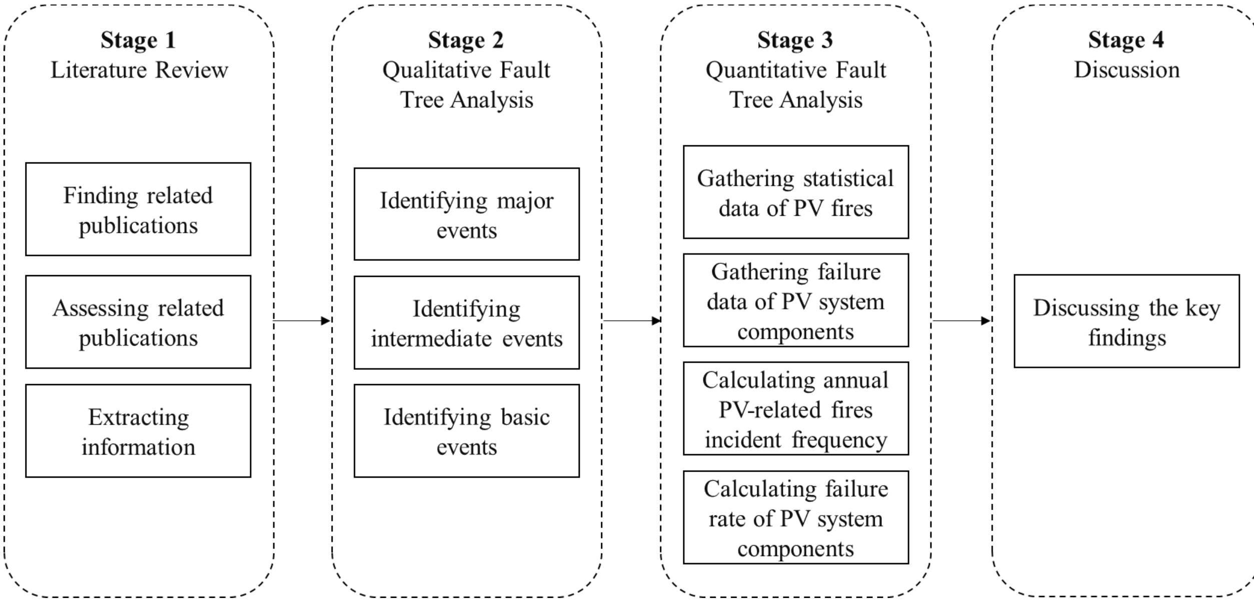

Fig. 1. Stages in computing the failure rate of PV-related fires.

In Stage 3, the failure rate data was needed for quantitative analysis in the fault tree diagram, where the number of fires was linked with the cumulative capacity of a given year. Data regarding annual PV-related fires were only available in the public domain for four countries; Australia [44], Germany [45], Italy [16], and the USA [46]. Due to national deviations, the data were not uniform, which is why the data were rearranged and harmonised. Although it is acknowledged that the amount of data is sparse, the analysis is deemed essential as it quantifies the overall global risk related to PV systems in the built environment instead of focusing on national events. It was also possible to find some data from the Netherlands, but since the current Dutch data set only consists of data from two years and ten months, it was not included in the calculation, but rather used for comparison in the discussion.

The number of fires caused by a specific PV system component was used to determine the contribution of that component towards a PV-related fire. During the current study, the data sets on the percentage of fires caused by specific components in PV systems were only available for three countries; the UK [19], Germany [45] and Australia [44]. These data sets were extracted from public domain resources. As the three data sets are not homogenised among them, the source of failure types leading to a PV-related fire was grouped according to the major events identified in the fault tree analysis. The average percentage of components initiating fire in the PV system was then normalised based on the incident frequency related to the specific components before getting the number of fires per MW per year by the PV component. Although the current data originates from Europe, North America, and Australia, until further data is available, there is no reason to believe that countries from other continents should have partially different results. That said, it should be emphasised that neither continent can be treated as a homogeneous area, as the stage of technological development varies from country to country and region to region. The key findings from both qualitative and quantitative fault tree analysis were thoroughly discussed in the final stage.

3. Results and Discussions

3.1 Qualitative Fault Tree Analysis

The fault tree top event is PV-related fires, including fires caused by the PV system itself and fires caused by unknown or external ignition sources. The wide definition is necessary due to the quality of the available data. As the data is not uniform, and in some cases based on non-standardised and non-compulsory comments regarding the presence of a PV system, the source of ignition is not determined in all the reported data. For the fires initiated by a PV system, the fault tree is separated into six major events, which are ignitions caused by an electric malfunction in the PV module, isolator, inverter, combiner box or fuse, cable, and connector. Finally, the seventh major event represents an ignition caused by an unknown event or an ignition source unrelated to the PV system. Thus, in the fault tree (Figure 2), the seven major events (including an undeveloped event) branch into seven intermediate and 41 basic events. The seven major events that can cause PV-related fires are connected with 'OR' gates since any of these events activate the top event autonomously. Table 1 describes the codes used in the qualitative fault tree diagram. The seven major events are further discussed in the following sections.

From the analysis of the first six major events, it can be concluded that electric arcing, where current flows across an air gap by ionising the air, is the main cause of the initial ignition related to the PV system. Consistent electric arcing is possible, as the PV system is based on direct current rather than alternating current. As such, the current is constant, which makes it possible for an arc to establish and sustain. High voltage arcs are extremely hot (> 6500 K) and can result in heating, and finally, ignition of nearby materials [47]. Arcing can be initiated where conducting parts become separated by mechanical movement or damage due to weathering, animals, or mishandling of the system during transportation and installation [19,20]. Moreover, when there is a build-up of contaminants like oxides on the electrical contacts, resistive heat is generated, resulting in the material breakdown that leads to arcing [19].

Table 1. Fault tree events and codes linked with the fault tree diagram presented in Figure 2.

Code	Event	Code	Event	Code	Events
S01	Ignition caused by PV module	A6	Damages from mountings	D1	Water ingress
S02	Ignition caused by isolator	A7	Excessive snow loads	D2	Loose screw terminals
S03	Ignition caused by inverter	A8	Vandalism	D3	Component damage
S04	Ignition caused by combiner box and fuse	A9	Thermal expansion or contraction	D4	Installation error
S05	Ignition caused by cable	A10	Metallisation distortion	E1	Pulling out of cables
S06	Ignition caused by connector	B1	Moisture ingress	E2	Weathering effects
S07	Unidentified or unrelated source of ignition	B2	Loose screw terminals	E3	Damages from animals
X1	Failure/Absence of fault detection and interrupting devices	B3	Installation errors	E4	Installation errors
X2	Arcing/Overheating	B4	Manufacturing defects	F1	Moisture ingress
X3	Module damage	B5	Damaged component	F2	Loose screw terminals
A1	Corrosion	C1	Moisture ingress	F3	Incorrectly crimped contacts
A2	Bypass diode failure	C2	Cable damage	F4	Physical damage
A3	Installation error	C3	Installation error	F5	Installation error
A4	Manufacturing defect	C4	Lack of ventilation	F6	Incompatible plugs and sockets
A5	Damages from frame distortion	C5	Manufacturing defects	F7	Poorly soldered joints

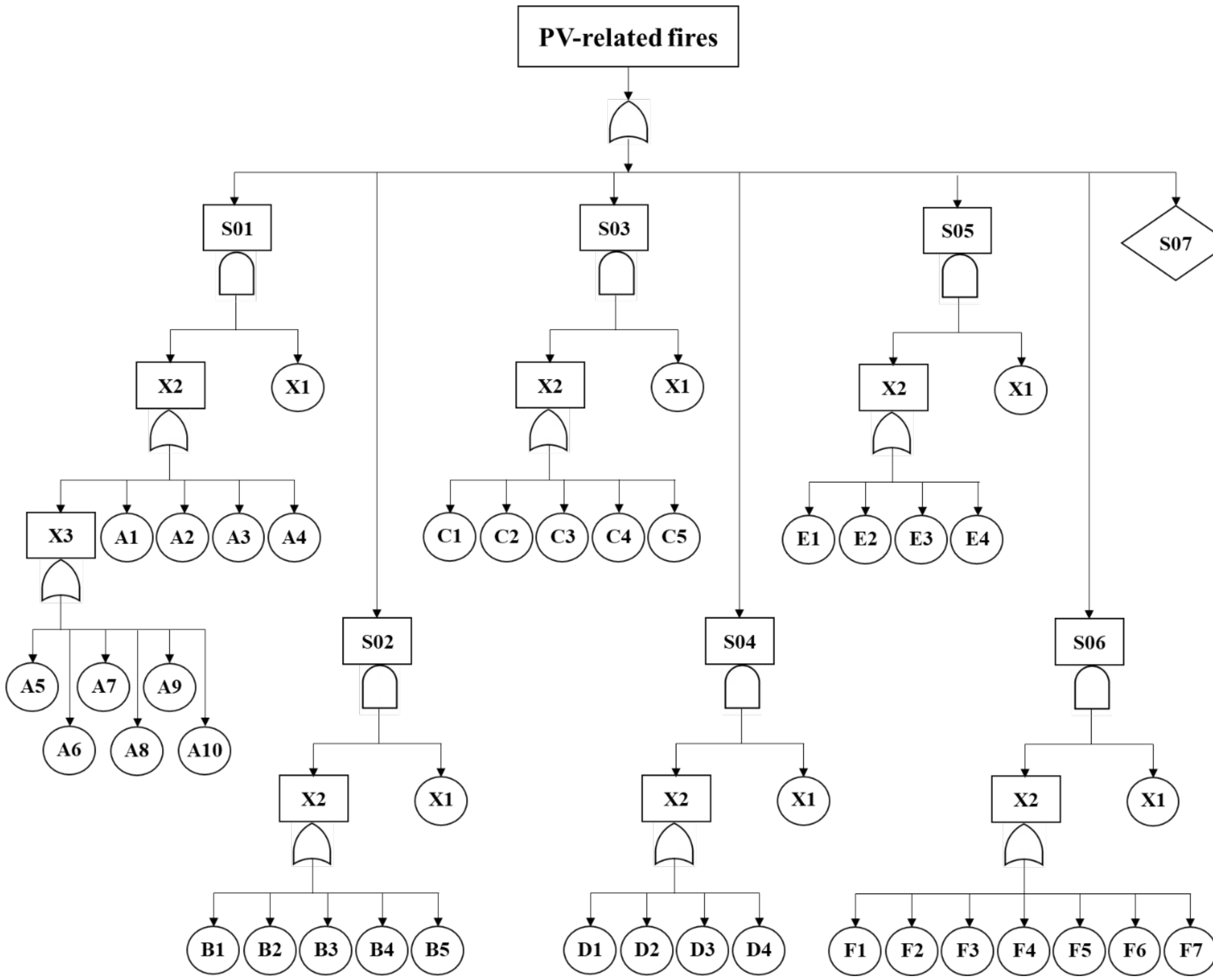

Fig. 2. Qualitative Fault Tree Diagram for PV-related fires.

3.1.1 S01: Ignition caused by PV Module

PV modules are the assembly of PV cells encapsulated within an anti-reflective layer of glass and plastic based back-cover. An aluminum frame usually protects the edges of the glass and provides mechanical strength to secure it with mounting structure. The auxiliary parts include interconnections, terminals, and diodes [48]. In PV modules, fire can be caused by arcing/overheating along with failure or absence of fault detection and mitigation. The basic causes of arcing or overheating in modules are physical damage of the module, corrosion, bypass diode failure, installation errors, and manufacturing defects.[19,20,45] In certain incidents where PV modules are suspected to be the source of fire, there is an indication of arcing in the remains of one or more of the modules [19]. According to a study, modules are a prominent cause of fire in PV systems [20]. Some modules in the market have been found to be faulty on account of manufacturing defects or faults occurring due to damage incurred because of poor packaging and transportation practices [20]. In some incidents, the mechanical design of the PV system is found to be flawed such that the modules got jammed together, causing electric arcs due to fracture [20]. The module junction box is a hot spot for initiating fire in modules which is due to deficient quality assurance during manufacturing resulting in product defects [45].

3.1.2 S02: Ignition caused by Isolator

The Direct Current (DC) switch or isolator is installed to cut off the DC supply between the PV arrays and the inverter when needed. As such, the inverter is not fed with DC current and does not supply AC current to the property. The Alternate Current (AC) switch is normally installed in the circuit between the inverter and the distribution board of the property. Similar to the DC switch, the purpose is to protect the fire and rescue services by eliminating electric circuits inside the property. In both AC and DC isolators, fire can be caused by arcing/overheating along with failure or absence of fault detection and mitigation. The basic causes of arcing or overheating in isolators are moisture ingress, loose screw terminals, installation errors, poor design and manufacturing defects as well as physical damage of the component [19].

3.1.3 S03: Ignition caused by Inverter

The inverter is a complex part of a PV system that actively manages and converts the direct current (DC) from the PV modules into alternating current (AC). Most of the PV-related fire incidents are not initiated by inverter failures. One of the reasons is because inverters are well equipped with sensors and excellent safety features that help prevent catastrophic failures [19]. According to the study by Coonick et al. [19], nine of 64 fires were initiated by the inverter defects. A study conducted by Chiaramonte [44] found that 21% of PV fires were originated from inverters. Inverter fire occurs when there is arcing or overheating in the absence or failure of fault detection and interruption devices. The basic causes for arcing and overheating in the inverter are found to be cable damage, moisture ingress, faulty switches, manufacturing defects, and installation error [20]. Unprotected installation of inverters outdoor with stress from temperature and condensation can also cause a fire in these components [20].

3.1.4 S04: Ignition caused by Combiner Box and Fuse

The combiner box in a PV system brings the output from numerous PV strings together. Each string cable lands on a fuse terminal, and the output of the fused inputs are combined onto a single conductor that connects the box to the inverter [49]. An arcing and overheating due to failure or absence of fault detection may cause sustained arcing and lead to a fire in the component [50]. A simple poor connection in the DC combiner box may lead to arcing and ignition due to poor installation practices and degraded connections resulting from water ingress. Another main reason for the poor connection is loose screw terminals in this component [19]. Laukamp et al. [45] revealed that the array junction box at the DC side of the PV system is a prominent cause of the fire as the screw terminals present in DC combiner box/DC junction box is a weak point, and it can be a reason of poor contact that may lead to ignition. Hence, Laukamp et al. suggested that the connection technology should be replaced with other connection technologies [45].

3.1.5 S05: Ignition caused by Cable

Studies in the UK and Germany have found that a notable number of fires related to the PV system are caused by electrical failure related to the cables [19,45]. Electrical cables are used throughout the PV system to combine the various components. As such, they are prone to damage from weathering effects, unintended physical strain, design errors, and animal bites, which is why they constitute one of the major events. All these factors may lead to arcing and overheating of cables that if not detected and interrupted by the fault detection and interruption devices can lead to an ignition in the system. Sepanski et al. [20] concluded that undersized cables caused a potential strain in the cables and damage on the connectors due to mechanical stress, whereas animal bites could damage the insulation, making it prone to arcing and short circuit. The consequences of cable insulation damage were also addressed by Alam et al. [24] who besides failures caused by rodents and physical impact damage, also mentioned corrosion, water leakage, and ageing as factors that could cause an ignition. The potential consequences of long-time weathering is an important factor is also mentioned by Strobl and Meckler [51].

3.1.6 S06: Ignition caused by Connector

Connectors and terminals, hereafter termed connectors, are found to be a frequent cause of faults in the PV system [19]. Combined with the cables, they are used to connect components, as well as to connect PV modules in series to increase voltage or in parallel to increase current. Sepanski et al. [20] concluded that there are several reasons that connectors can be a source of arcing, and thus ignition and fire, in which incorrect crimping, loose screw terminals, incompatible plug and socket, installation errors, poor soldering joints, connectors not fully inserted, and poor assembly of the plug (i.e. contact leg of the plug may slip without coming into the notice of installer after insertion and physical damage is the most common installation error associated with connectors). Furthermore, Sepanski et al. [20] revealed that cross-connection between connectors from different manufacturers is a potential source of ignition, as visual looks, and the fact that multiple brands can be cross-connected does not guarantee an ideal electric connection with the same lifespan as connections between two plugs designed for each other. In such cases, contact resistance increases with time which leads to overheating of the contact and finally converts into an arc. Von Balmoos [52] compared the resistance between the reference PV connector, MC4, manufactured by Stäubli, and a series of cross-connections. Compared to the reference connection, the average resistance was twice as high in the worst cross-connection post assembly. To examine the consequences of artificial ageing a test-cycle equivalent to IEC 62852:2014 E2 were used, and it revealed one fifth resistance increase for the reference connection (121.5%), whereas the resistance of the worst preforming cross-connection was almost four times the resistance of the reference connection post assembly (398%) [52]. Apart from these reasons, if contact is exposed to moisture, it can cause corrosion which may lead to resistive heating that can be a precursor to arcing [19].

3.1.7 S07: Unidentified or Unrelated Source of Ignition

Contrary to the previous six major events, the seventh event is categorised as the undeveloped event where it indicates that the event could be refined and broken down further. The final major event contains two sources of ignition: (i) an ignition caused by an unknown component in the PV system, and (ii) an ignition source not related to the PV system. In the studies from where statistical fire incident and investigation data has been taken, there are certain fire events in which fire was not traced to a particular component on account of restriction of access of first responder or investigators to the scene due to safety reasons or failure of the forensic laboratory to determine the exact ignition point in the PV system. Furthermore, all PV-related fires are not necessarily caused by an ignition in the PV system itself. As for other rooftop fires, the fire might be caused by an external source of ignition, such as a fire inside the building or burning embers from a nearby structural fire or wildfire. Although the PV system does not cause the fire, the presence of the PV modules as a physical object can modify the fire dynamics of the roof construction and thus, facilitate the spread of fire. The final major event is the only event in the fault tree analysis where the probability of ignition cannot be reduced by factors related to the PV system. As such, the risk related to the final major event can only be reduced by mitigating the consequences in case of ignition.

3.2 Quantitative Fault Tree Analysis

The quantitative fault tree diagram shown in Figure 3 is based on all publicly available data regarding PV-related fires, which was globally accessible by 2021. Naturally, the analysis can be improved as the current countries increase the amount of data and as more countries include the PV system as a possible source of ignition in their post-fire evaluation schemes. As such, the fault tree analysis is, to the knowledge of the authors, the best quantitative analysis possible based on all accessible data as of 2021. The main objective of performing a quantitative analysis is to find the failure rate of PV systems due to fire incidents and identify the most significant components contributing to PV-related fires. Figure 3 presented seven major events which are connected with the top event through the 'OR' gate. Quantitative fire risk in this study is formed by the national number of PV-related fires in a year in relation to the total installed national capacity. The national capacity of PV systems was preferred to the amount of PV systems in each country, as the qualitative fault tree analysis concludes that the probability of ignition increase with the number of components. Whereas the number of components in a single PV installation can vary between less than a hundred to several thousand depending on whether it is a small domestic or a large commercial installation, the correlation between power capacity and the number of components is more reliable. Hence, installed capacity can be correlated with the number of components, and thus the probability of PV-related fires.

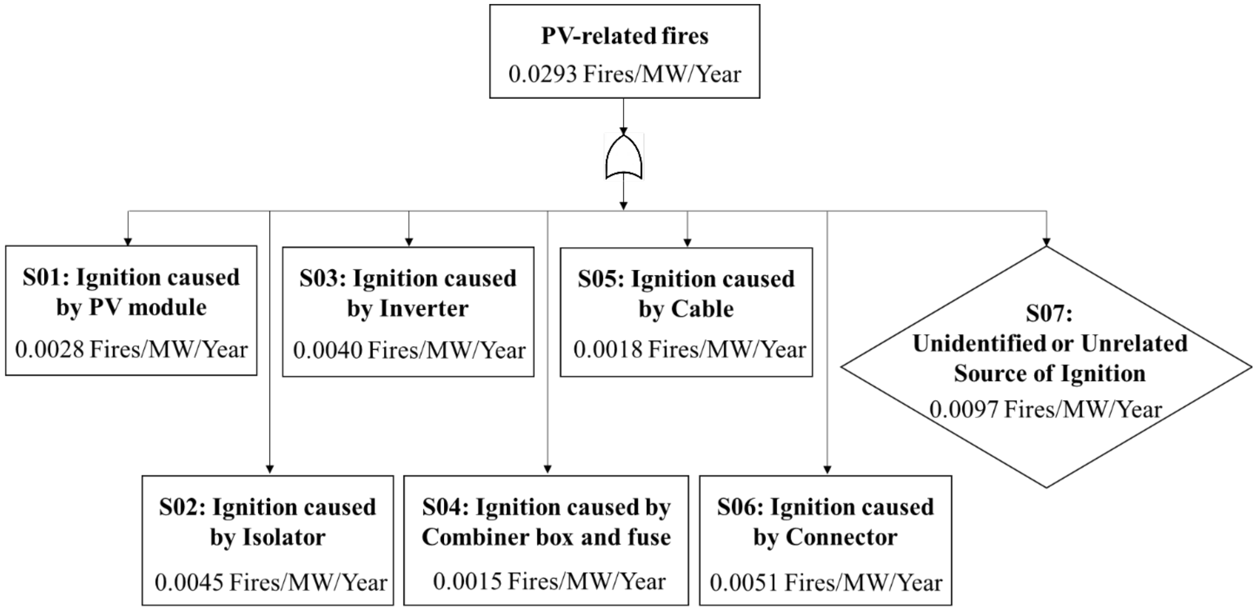

Fig. 3. Quantitative Fault Tree Diagram for PV system fires.

The annual frequency of PV-related fires, which is based on the data in Table 2, is plotted in Figure 4, where the difference between the four countries is very obvious. With a single exception, the frequency never exceeds 0.0051 fires per MW per year in neither Germany nor the United States, whereas the majority of frequencies in Australia and Italy are above 0.015 fires per MW per year. By the first look, the difference between the four countries is striking, but it is justified by how the data are obtained. In both Italy and Australia, the fire and rescue service have had a specific check-box in their post-fire evaluation reports, whereas the PV-related fires in the USA and Germany are, respectively, reported in the National Fire Incident Reporting System (NFIRS) and through a voluntary questionnaire to relevant stakeholders. Ideally, the data from NFIRS should be as reliable as the incident reports from Italy and Australia. However, according to Kinsey and Ahrens [53], aspects of NFIRS are unnecessarily complex and challenging in ways that undermine the quality of data and, ultimately, decisions based on that data.

Such conclusions, combined with a general uncertainty regarding the quality of the available data, question the value of any further analysis, as the fire incident reports from at least Germany and the USA do not cover all fires related to PV systems. Ultimately, it can be concluded that the actual risk of fires related to PV systems will be higher than the calculated risk herein. To compensate for the inconsequent quality of the incident reports, an average annual frequency of 0.0293 fires per MW is calculated as a weighted mean with respect to the number of fires each year. Using the weighted mean instead of the arithmetic mean ensures that every single incident contributes equally. As such, data from countries with a more consequent report system, and thus more incidents, is not diluted, which would happen if the overall frequency were calculated as an average of the incident frequencies in Figure 4.

Table 2. Input data and calculation of the overall number of PV-related fires per MW capacity per year for four countries. The table also includes an overall average.

Country	Year	Overall

		Number of Fires	Cumulative Yearly Installed Capacity [MW]	[PV-related fires/MW]	Weighted Average [PV-related fires/MW/year]	Weighted Average [PV-related fires/MW/year]
Germany [2,45]	2008	7	6120	0.0011	0.0016	0.0293
	2009	18	10566	0.0017		
	2010	20	18006	0.0011		
	2011	47	25916	0.0018		
	2012	53	34077	0.0016		
Italy [4,16]	2008	20	496	0.0463	0.0326	
	2009	30	1277	0.0262		
	2010	75	3605	0.0216		
	2011	280	13141	0.0219		
	2012	780	16796	0.0473		
	2013	585	18198	0.0324		
	2014	440	18607	0.0238		
	2015	461	18915	0.0244		
Australia [44,54]	2009	3	189	0.0248	0.0268	
	2010	3	578	0.0059		
	2011	9	1444	0.0065		
	2012	41	2491	0.0168		
	2013	84	3283	0.0258		
	2014	146	4131	0.0358		
	2015	106	5057	0.0213		
United States of America [46]	2009	6	1188	0.0051	0.0010	
	2010	2	2017	0.0010		
	2011	7	3937	0.0018		
	2012	11	7130	0.0015		
	2013	19	12076	0.0016		
	2014	11	18321	0.0006		
	2015	8	25821	0.0003		
	2016	14	49973	0.0003		
	2017	21	51818	0.0004		
	2018	29	62498	0.0005		

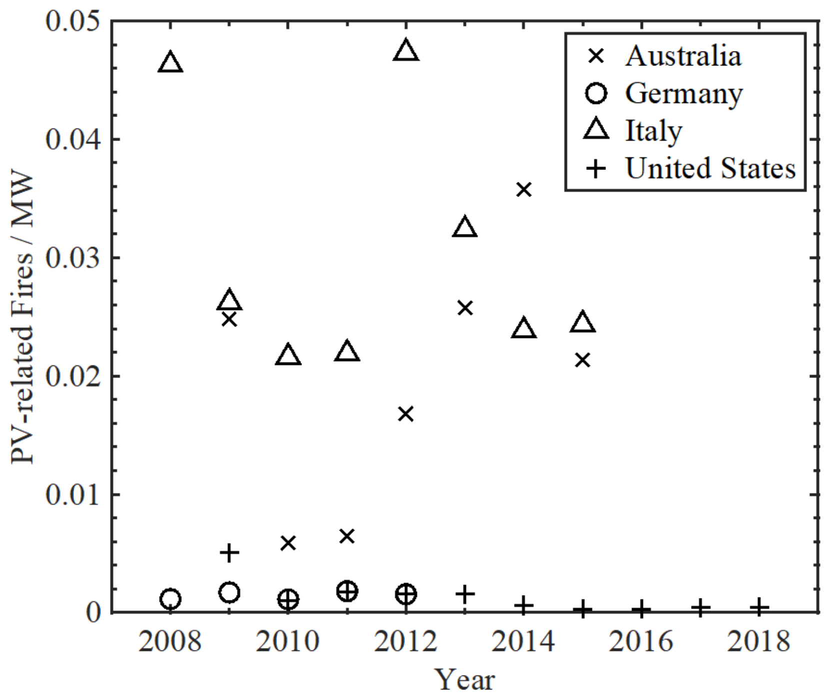

Fig. 4. Annual PV-related fires per MW installed capacity ranging from 2008-2018 for four countries.

Based on the Dutch cumulative capacity of 4.5 GW (2018) and 6.9 GW (2019), it would cause an expectation of 131 and 199 PV-related fires, respectively [2]. As only 29 PV-related fires were registered both years, it can be argued that fire incident frequency of 0.0293 fires per MW per year is an overestimation [17]. However, the Dutch data is only based on incidents reported by the (social) media, which is why it is expected to be underreported, similar to the data from the USA and Germany [17]. This also corresponds with the Dutch frequencies of 0.0066 and 0.0043 fires per MW per year, which is slightly higher than most of the annual frequencies from Germany and the USA. As such, the calculated global fire incident frequency of 0.0293 fires per MW per year is deemed to be representative for the actual number of PV-related fires.

To determine the incident frequency related to the specific components, data regarding the percentage of fires due to specific components in a PV system is extracted from reports from 64, 174 and 400 PV-related fires in the UK [19], Germany [45] and Australia [44], respectively. The components related to ignition are not harmonised among the three data sets, which why the failure types were grouped into the seven major events in accordance with Table 3. Common for the three data sets are the major events S01-S03. When comparing the data types, it is noteworthy that the German data have 18 subcategories related to the PV installation, whereas the Australian data set is limited to ten. Consequently, no PV-related fires in Australia are related to the major events S04-S06 and a large majority of ignition sources causing fires are categorised as undefined or unrelated ignition sources (S07) which is an unused category in the German data set. By studying the subcategories grouped into the Australian major event S07, it is evident that neither of the categories labelled as 'exterior others', 'in-house', or 'batteries' are related to the PV system itself. However, it is stated in the report that although the PV system did not cause the ignition, the fires are categorised as PV-related as the PV systems were included in the subsequent fire. It is also stated that the remaining categories within the Australian S07 can be caused by the PV system, and therefore include the major events S04-S06.

Table 3. Grouping of failure types leading to a PV-related fire based on data from the UK [19], Germany [45] and Australia [44].

Major event and components		Failure type grouping		
		UK	Germany	Australia
S01:	Ignition caused by PV module	PV modules	Module, Junction box, Cell connector	Exterior roof/Solar panel
S02:	Ignition caused by isolator	DC isolators	DC switch, AC switch	Isolator
S03:	Ignition caused by inverter	Inverters	Inverter electronics, Inverter, Transformer, AC distribution	Inverter/Switchboard/ Overload
S04:	Ignition caused by combiner box and fuse	DC combiner box	DC fuse, Generator junction box, AC fuse	N/A
S05:	Ignition caused by cable	DC cables	DC cable	N/A
S06:	Ignition caused by connector	DC connectors	Crimping, DC terminal, AC terminal, DC plug, AC plug	N/A
S07:	Unidentified or unrelated source of ignition	Unidentified components	N/A	Batteries, Exterior Other, In-House, Other, Deficiency/Failure Electrical, Unknown

For the German data set, the lack of the fires caused by an unknown source of ignition (S07) might be a consequence of the method used to obtain the data or an active choice not to include all PV-related fires, but only the fires caused directly by the PV system itself. As such, the data sets are not only inhomogeneous with respect to the subcategories but also with respect to whether or not each of the datasets contains subcategories that can be included within all of the seven major events, which is the reason that the major events S04-S07 only contain data sets from the UK and Germany. To work around the inhomogeneous data, the average probability of major events S04-S07 was calculated as the average of two values, whereas the remaining major events were calculated as the average of all three data sets. Consequently, the sum of calculated averages was 126%, which was subsequently normalised in Table 4 and plotted in Figure 5.

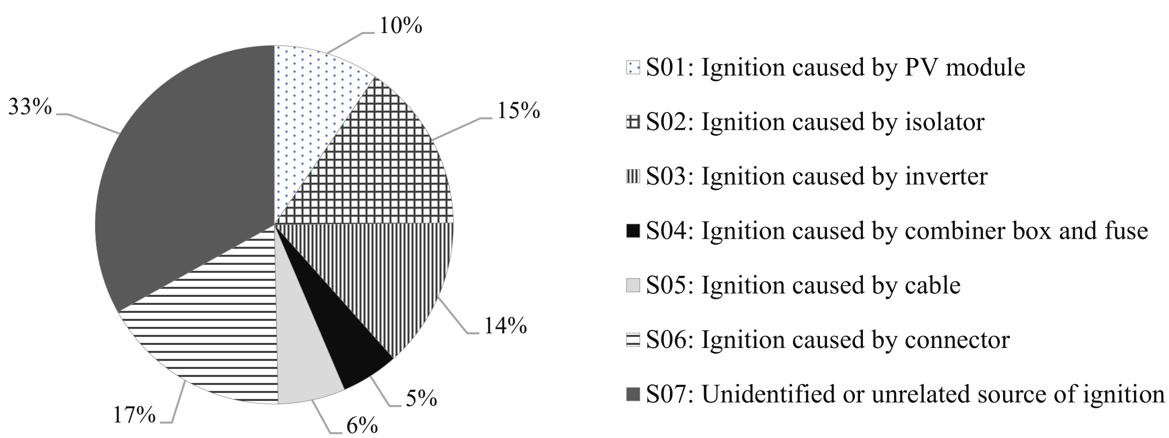

Fig. 5. Normalised contribution of PV system components towards PV-related fires.

Table 4. Calculation of number of fires per MW per year by PV system components based on data from the UK [19], Germany [45] and Australia [44].

Major event and component that are believed to be the initiating cause of fire in PV system	Countries from where data of components are taken that are blamed to be the initiating cause of fire in PV system			Normalised average percentage of component initiating fire in PV system (%)	Number of fires per MW per year by PV component (Normalised average percentage of components initiating the fire × 0.0293 fires/MW/year)
	UK (%)	Germany (%)	Australia (%)		
S01: Ignition caused by PV module	8	24	4	10	0.0028
S02: Ignition caused by isolator	44	8	6	15	0.0045
S03: Ignition caused by inverter	14	24	13	14	0.0040
S04: Ignition caused by combiner box and fuse	2	11	N/A	5	0.0015
S05: Ignition caused by cable	8	7	N/A	6	0.0018
S06: Ignition caused by connector	19	25	N/A	17	0.0051
S07: Unidentified or unrelated source of ignition	6	N/A	77	33	0.0097

Based on the normalised averages, five of the seven identified major events stand out. Modules, isolators, connectors and inverters account for around 10% to 17% of the ignition sources causing PV-related fires, whereas the unidentified or unrelated ignition sources are related to 33%. The latter might be due to the unavailability of data from Australia, as the study include several external sources of ignition and does not specify any fires directly related to combiner boxes, cables, or connectors [44]. Together with the PV modules, the number of connectors is proportional with the capacity of the PV system, and it is assumed that the quantity of PV modules and connectors are significantly higher than the quantity of isolators and inverters, which indicate a higher failure rate of the two last-mentioned components despite the similar failure frequency. Common faults for the isolators are that they are vulnerable to human errors during both the design and installation process. The consequences of human mistakes, or rash shortcuts, were highlighted in the report by Coonick et al. [19] who recorded the use of AC isolators for DC current, as well as numerous examples of moisture ingress due to unauthorised fixation or installation of cables. In that report, the authors were able to identify the root cause for 18 of the incidents of which 13 were related to poor installation and therefore a consequence of carelessness or poor understanding of the risk related to PV systems [19]. The findings correspond with a survey conducted in Australia, where it was found that 82% of the PV installers believe that isolators are the major cause of fire in PV systems [44]. Sepanski et al. [20] state that the frequency of fires caused by the inverter is no surprise, as it is the most complex component of the PV system and thus, most likely to fail. According to Coonick et al. [19], the inverter caused relatively fewer fires in the UK because it is an "intelligent" component compared to the isolator.

Although the quantity of connectors is large, it is assumed that most of them are preinstalled at the cable ends of the PV modules, which means that they are less prone to human errors. The pre-installation also entails that cross-connections are less likely if the connected PV modules are of the same type. Nevertheless, the connectors are also used for the rest of the PV system infrastructure where the distance between PV strings, PV arrays, combiner boxes, isolators and inverters are case-specific and depends on the hosting roof construction. As such, some of the connectors are manually installed, which increases the probability of failure and thus, potential ignition. This is highlighted by the failure types described in the qualitative fault tree analysis.

Compared to the other major events, the fires caused by an unknown or unrelated ignition source (S07) is significant. The normalised average of the three data sets is 33% and due to the previously discussed differences between the German and Australian data sets, it is deemed that the data is representative for the frequency of fires caused by the major event S07. The findings indicate that the risk related to 33% of the global PV-related fires cannot be reduced by an improved focus on a specific component of the PV system. Partly because some of the fires were caused by an unknown PV component, and partly because some of the PV-related fires were ignited by an external source of ignition. If it is assumed that all fires caused by the major event S07 are linked to an external source of ignition, it can be derived that the PV system increases the probability of ignition by a factor of three compared to a roof construction with no PV system, as two PV-related fires are caused by the PV system every time one fire is caused by an external source of ignition. However, such a conclusion entails that the consequence of ignition is not affected by the introduction of the PV system as a physical object, which does not correspond with the findings of Ju et al. [32], Kristensen et al. [22], Meacham and McNamee [46], or guidelines from FM Global [55]. Although the amount of research concerning the consequences of a PV-related fire is limited, it is evident that the PV system alters the fire dynamic system of the roof, whereupon a roof construction designed in accordance with a known piece of legislation, such as UL 790 [30] or EN 13501-5 [31], is compromised. As such, it can be concluded that the introduction of a PV system upon a roof construction boosts the risk significantly, as both the probability of ignition and the consequences are enhanced.

The enhanced consequences in case of ignition are not only relevant if the ignition is caused by an unknown source (S07) but also for the remaining 67% of the 638 incidents included in the quantitative analysis (S01-S06), as a well-designed fire dynamic solution is unaffiliated from the source of ignition. As such, the result of the quantitative analysis can be separated into two main findings. First, it is concluded that the most effective reduction of the fire-related risk of building applied PV systems is to mitigate the consequences in case of ignition, as a mitigation of the consequences will reduce the overall risk independent of the ignition source. Second, a combination of the frequencies and failure types described in the three reports containing the datasets used in the quantitative analysis indicates that the probability of ignition related to the module (S01), isolator (S02), inverter (S03) and connector (S06) can be reduced with an increased focus on the installation process. An increased focus is time-consuming and thus expensive, which does not correlate well with the fact that cost reduction is a key parameter to reach terawatt-scale photovoltaic power production and competitiveness with energy produced by fossil fuels [6]. In the USA, the cost of commercial PV installations dropped by 69% between 2010 and 2020, mainly due to an 85% module price drop [56]. During the same decade, the labour cost increased from 5.7% to 8.7% of the total cost, as it only dropped by 53% [56,57]. The reduced labour cost is assumed to be caused by a faster installation process and/or a less qualified, and thus less expensive, workforce.

Based on the findings in the qualitative and quantitative analysis of the failure modes and frequencies, where the module (S01), isolator (S02), inverter (S03) or connector (S06) cause a fire, it is worth considering if a continued labour cost reduction is beneficial. The upfront cost of the commercial PV system might be reduced, but if it is assumed that a reduced labour cost entails a less qualified or focused workforce, the PV system might have an increased amount of failures which can affect the system efficiency. From an economically sustainable point of view, a reduced efficiency will cause a lower production, whereas an increased probability of failure is the main concern with respect to fire safety and property protection.

By 2019, the cumulative installed PV capacity exceeded 3 GW in 15 out of 27 member countries of the International Energy Agency (IEA) Photovoltaic Power Systems Programme (PVPS) [2], which corresponds to an assumption of at least 100 PV-related fires in each country according to the calculated quantitative frequency. However, it is difficult to verify the findings as no countries as no relevant data is obtained, or published, by the national fire and rescue services in 25 of the 27 member countries. The difference in the annual frequencies obtained in Italy and Australia compared to Germany, the Netherlands, and the USA, emphasise that the frequencies and the level of detail strongly depend on the acquisition method. Due to the potential number of PV-related fires in the IEA PVPS member countries, a global harmonisation of the recording method will be ideal, as it will increase the understanding of the fire-related risk associated with the technology which will benefit all stake holders. The benefit for the property owners, owners of the PV systems and society will be instant, whereas the PV industry will profit in the long run as an increased understanding of any potential risk give rise to a sustainable technology and thus business model.

Homogeneous data acquisition involves uniform response options from similar responders, which suggest the national fire and rescue services as recommended responders. To determine the ignition source and with it, the cause of the fire, it might require an in-depth forensic investigation, which is not necessarily part of the basic response from all fire and rescue services. Thus, it is suggested that the response options are divided into two levels. Initially it is of interest to know if the fire was related to the PV system, which does not imply that the fire was caused by the PV system. The use of the term “related to” instead of the term “caused by” is preferred for two reasons: (i) it is not always possible to determine the cause of ignition, which is why the term “caused by” might exclude some fires caused by the system and thus, dilute the data, and (ii) The consequence of a fire is similar no matter the source of ignition, as the PV system, as a physical object, modifies the fire dynamics of the roof construction and thus, the flame spread behaviour upon the building envelope. The source of ignition could be addressed in the subsequent question, which should be divided into multiple response options. Eight response options are suggested based on the seven major events, as it is recommended to separate the major event “S07 Unidentified or unrelated source of ignition” into the following two response options: (i) “Ignition caused by unknown PV component”, and (ii) “Ignition not caused by the PV system”.

4. Conclusion

Rooftop PV systems are promising electrical power sources and a potential fire risk at the same time. In the qualitative fault tree analysis, seven major events were defined as the potential ignition sources leading to the major event, a PV-related fires. Herein, it was found that arcing is the major contributor of fire events, which arise from poor-quality products, planning and installation errors, component damages during transportation, operation errors, lack of regular inspection and maintenance, as well as weathering effects. The less prefabricated the components and designs are, the more likely the probability of human errors, which makes the components prone to electric malfunctions and thus, a probable source of ignition.

Based on the four national data sets publicly available by 2021, a quantitative analysis revealed an average annual frequency of 0.0293 PV-related fires per MW installed capacity. The quality of the data sets was inconsistent due to the sampling methods, which caused a significant variation between the frequencies observed in Australia, Germany, Italy, and the USA. Consequently, it was decided to calculate the average based on the weighted mean rather than the arithmetic mean, whereupon each fire affected the average equivalently – no matter the geographic location of the fire. Compared to recent data from the Netherlands, the calculated frequency tends to be an overestimation. But since the Dutch data is entirely based on fires reported in the (social) media, it is deemed that the calculated frequency is an acceptable estimation for the total number of PV-related fires. With an increased amount of data from the national fire and rescue services, it will be possible to verify, or adjust, the calculated frequency, which will benefit all stakeholders as an enhanced understanding of the risk, and how to mitigate it, will cause an increased faith in the long-term sustainability of the technology – from an environmental and economic point of view. The fire incident frequency associated with specific PV components were extracted and normalised from three reports which summarising the result of fire investigations in Australia, Germany and the UK. Based on the normalised data, the quantitative analysis indicated an over-representation of fires caused by an ignition linked to either the PV module, isolator, inverter or connector, which corresponds well with the findings of the qualitative analysis.

In one-third of the PV-related fires, the ignition source was either unknown or unrelated to the PV system, which emphasises that an increased focus on mitigating the consequences in case of ignition might be the most effective way to reduce the overall fire-related risk of building applied PV installations. It is concluded that an increased understanding of the modified fire dynamics, combined with better design and installation practices, can significantly reduce the risk. As PV systems are usually installed for a long-term usage, it would be interesting to investigate if and how weather and aging process of PV components contribute towards PV-related fires. Finally, two questions are suggested for implementation into the post-incident report of the national fire and rescue services, as a homogeneous data set will increase the overall quality of future analyses.

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