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FIRE SAFETY OF PV SYSTEMS

INSIGHTS AND RECOMMENDATIONS

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Business Unit Solar Energy / System Technology

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TABLE OF CONTENTS

1 INTRODUCTION

Recently, unsubstantiated safety concerns were created by the media about the safety of PV systems, despite photovoltaics being an extremely safe technology. Rumors about burning houses that cannot be extinguished or firefighters who do not fight a fire if PV is involved put rooftop PV systems in a light they do not deserve. In fact, PV systems are of a very high safety level when it comes to preventative fire protection as well as operational safety and security in the case of fires. Many recent analyses of fire incidents related to PV, like those from TÜV Rheinland and Fraunhofer ISE (Sepanski et al., 2015), BRE (2017b), and IEA PVPS (2017) show that components of PV systems are tested according to very stringent safety and reliability test protocols during the manufacturing process. This ensures they fulfill electrical safety requirements of various national and international codes and standards. Additionally, aspects like the creation of fire compartments, accessibility, functional integrity, and mechanical safety have to be considered in planning, construction, and operation. Modules that act as a part of a roof (building integrated PV) have to fulfill the same fire resistance tests as the roofing material.

According to the International Energy Agency Photovoltaic Power Systems Program (IEA PVPS), *“PV systems do not pose health, safety or environmental risks under normal operating conditions if properly installed and maintained by trained personnel as required by electric codes.”* (IEA PVPS 2017; p. 2).

1.1 Objective

The aim of this paper is to evaluate and display the actual situation concerning fire incidents including a PV system in selected countries and to derive if there is a significant contribution of building related PV systems to the risk of fire. Although PV is a very safe technology and incidents are rare, this analysis should highlight the most common reasons for arc faults and therefore possible fire incidents. Based on the findings of this failure analysis in selected countries, suitable measures for reducing the already small fire risk induced by PV systems are derived.

Although low voltage electricity has been a part of almost every building for decades now, and fire fighters know how to deal with it, a certain precariousness exists in the public when it comes to the topic of extinguishing a PV related fire. By analysing different operation tactics and strategies as well as safety measures to reduce the risk of electrocution for firefighters, this paper provides recommendations on how to act in the event of a fire.

1.2 Fire and PV Systems: Fact and Fiction

As mentioned in the introduction, rumours about rooftop PV systems and their handling in the case of fires still exist. By analysing customer feedback, headlines as well as relevant literature (Sepanski et. al. 2015), the following points have been identified, representing the variety of **incorrect information** that circulates in the public domain:

- Firefighters do not extinguish a fire in buildings with a rooftop PV system
- A rooftop PV system massively increases the risk of fire

- A rooftop PV system massively increases the risk of injuries during an emergency for firefighters
- Module level shutdown reduces the risk of fire
- It is not possible to extinguish a fire caused by PV
- A rooftop PV system greatly increases the possibility that a building gets struck by lightning

Next to the objective defined in Chapter 1.1, the listed points should be analysed critically, to check if there are realistic statements that confirm or invalidate those rumours.

1.3 Risk of Fire vs. Risk for Firefighters

Before going into detail regarding the analysis of PV related fire incidents, a distinct definition is necessary regarding the risks related to a fire.
When talking about the safety of PV systems, possible risks relating to a fire that may occur can be divided into two categories:

- **Risk of fire:** This risk describes the probability that a fire occurs. The higher the probability, the higher the risk that a fire occurs.

- **Risk for emergency responders:** This risk describes the probability that a firefighter or other emergency personnel is injured during a rescue or fire-fighting mission.

These two categories are both important when talking about increasing the safety of PV systems.
Taking appropriate measures to reduce the risk of fire directly reduces the risk for emergency responders, as no fire means no risks for the emergency responders, and therefore this should be the top priority as far as PV fire safety is concerned. This conclusion is not always applicable the other way around. Measures that directly affect the risk for emergency responders, like module level shutdown for example, often do not contribute to reducing the risk of fire, but could instead lead to an increased risk of fire as will be discussed in Chapter 3.

In its commitment to increase the already high level of safety concerning fire protection, Fronius sets the focus on decreasing the risk of fire, which directly influences the risk for emergency responders, therefore making it a sustainable and more beneficial approach.

2 FAILURE ANALYSIS

As mentioned in the introduction, this chapter will give an overview about fire incidents involving building related PV systems in selected countries.

2.1 Germany

Germany is one of the oldest PV markets worldwide, and the biggest in Europe. In 2015, TÜV Rheinland in cooperation with Fraunhofer Institute for Solar Energy Systems (ISE) published a report about fire incidents involving building related PV systems until 2013 and their causes. This detailed analysis showed that 430 instances of fire/heat damage were officially reported, whereof 210 were triggered by the PV system itself. Compared to the 1.3 million PV systems installed in total as of 2013, this equates to 0.016% of all PV systems installed in Germany (Sepanski et. al. 2015). The following figures show an allocation of the fire incidents to various types of error and error sources.

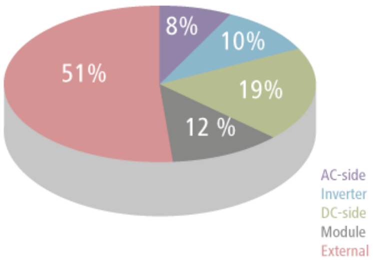

Figure 1: Error source – allocation for Germany (data from Sepanski et. al. 2015)

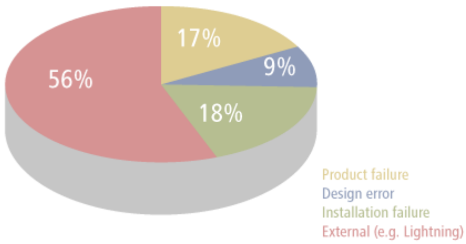

Figure 2: Type of error – allocation for Germany (data from Sepanski et. al. 2015)

The analysis showed that more than 70% of the errors are based on external influences or installation failures (see Figure 2). Whereas only 17% of the errors resulting in fire are based on product failure (see Figure 2) and only 10% of the errors occur in the inverter (see Figure 1).
A detailed fault analysis pointed out the most common reasons for serial arc faults, which are the main causes of fire incidents involving PV systems. These reasons are listed in Table 1, and sorted according to component and likelihood of occurrence.

Table 1 Possible reasons for arc faults, sorted according to component and likelihood of occurrence (Sepanski et. al. 2015)

Component	**Possible reason for arc fault**
DC-connector	Connector poorly crimped on site
	Mismatch of DC-connector
	Connector not fully inserted
	Connector mechanically damaged or corroded due to improper installation, weathering, animal bites, or production failure
	Connector poorly crimped in production
Screw terminals in field distributor, inverter (DC-side)	Screwing contact tightened inadequately, inadequate insertion of cable
	Undersized, arranged too close to each other
	Clamped cable-insulation
Solder connection (in module)	Bad solder connection, aging due to mechanical/thermal stress
Bypass diode	Overvoltage due to lightning storm or switching operation in system
	Long-term failure due to thermal overload
Module	Cell damages (micro cracks, …)
	Torn-off cell connectors
	Cell breakage/glass breakage
DC-fuses	Unsuitable fuses
	Incorrect installation
DC-cable	Long-term failure due to weathering (UV-radiation, humidity, temperature change, …)
	Damage due to improper installation (kink, …)
	Animal bites
DC-circuit breaker	Not suitable for DC
Junction box	Bad solder connection
	Aging due to mechanical/thermal stress
General installation	Improper protection class (humidity, dust)
	Top down cable insertion in PG-gland

The analysis showed that, next to external error sources, most of the errors that lead to fire incidents were due to installation failure on the DC-side of the PV system, the most common being the DC-connectors, which connect the PV modules of an array.

2.2 United Kingdom

In 2017, a detailed report about fire incidents involving building related PV systems was published by the BRE National Solar Centre.

According to this report (BRE 2017a), 58 fire incidents involving building related PV systems were reported since 2010 compared to a total of around 1 million PV systems installed in the UK. This is equivalent to 0.0058% of all installed PV systems in the UK. The following figures represent various types of errors and error sources pertaining to fire incidents.

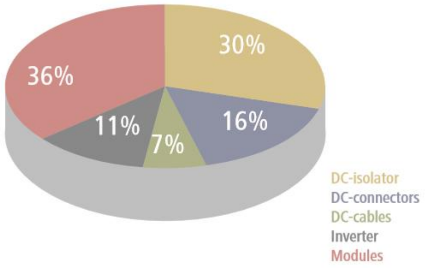

Figure 3: Error source – allocation for the UK (data from BRE 2017a)

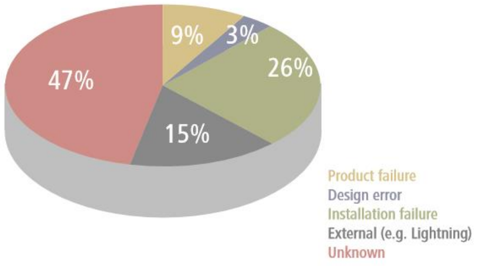

Figure 4: Type of error – allocation the UK (data from BRE 2017a)

Excluding the category “Unknown type of error”, most of the fire incidents are based on external influences and installation failures. Only 9% of all fire incidents are verifiably based on product failure (see Figure 4).

The following list shows the main causes of arcing identified in the report (BRE 2017a), many are related to issues with DC connectors. Contrary to the list in Table 1, this list is not sorted to likelihood of occurrence.

- Moisture ingress causing a degradation of connections in connectors, junction boxes, and switches
- Incorrectly crimped connector contacts
- Mating of incompatible connectors and sockets
- Connectors and sockets are not fully engaged
- Screws not fully tightened or loose screw terminals within junction boxes or isolator switches
- Poorly soldered joints within a PV module junction box or other junction box defects
- Damage to a component (e.g. broken busbars within a PV module)

Similar to the results of Germany (see Chapter 2.1), the analysis of the fire incidents involving building related PV systems for the UK showed that, next to external error sources, most of the errors that lead to a fire incident are due to installation failure on the DC-side of the PV system. DC-connectors were found to be a highly vulnerable component subject to installation faults, and the related issues are highlighted in the next chapter.

3 DC-CONNECTORS – NECESSITY AND ERROR SOURCE

Both studies presented identified that DC-connectors are one of the main causes for serial arcs in a PV-array. Other countries such as the Netherlands (ECN TNO 2019) and Italy (Corpo Nazionale dei Vigili del Fuoco 2015), have also reported that problems with DC connectors are a major cause for failures that can lead to a fire. In recent fire events in the US which involved rooftop PV installations on several Walmart stores between 2012 and 2018, connectors were similarly considered as the most likely root cause that triggered the fires (Roselund, PV Magazine 2019, Lopez, Business Insider 2019).

The two main root causes for the occurrence of serial arcs in DC-connectors are:

- Installation errors: Connectors not properly inserted together and poor attachment of connectors to cables.
- Connections realized with connectors from different manufacturers (mismatching).

This chapter will further address the main problems with DC-connectors.

3.1 Installation Errors

Human error is considered to be the principal cause of fires (Sepanski et al. 2015, BRE 2017c, p. 10). The most common types of installation faults include connectors which are not fully inserted, as well as poor on-site crimping of the connectors onto cables, both resulting in bad connections with higher transition resistance, which significantly increase the risk of arcing. Typical error sources include:

- Use of incorrect crimping tools, such as combination pliers (Figure 5), or cheap, low-quality pliers.
- Lack of precision when mounting of connectors, e.g., due to time pressure or uncomfortable conditions.
- Insufficient training of installation personnel.

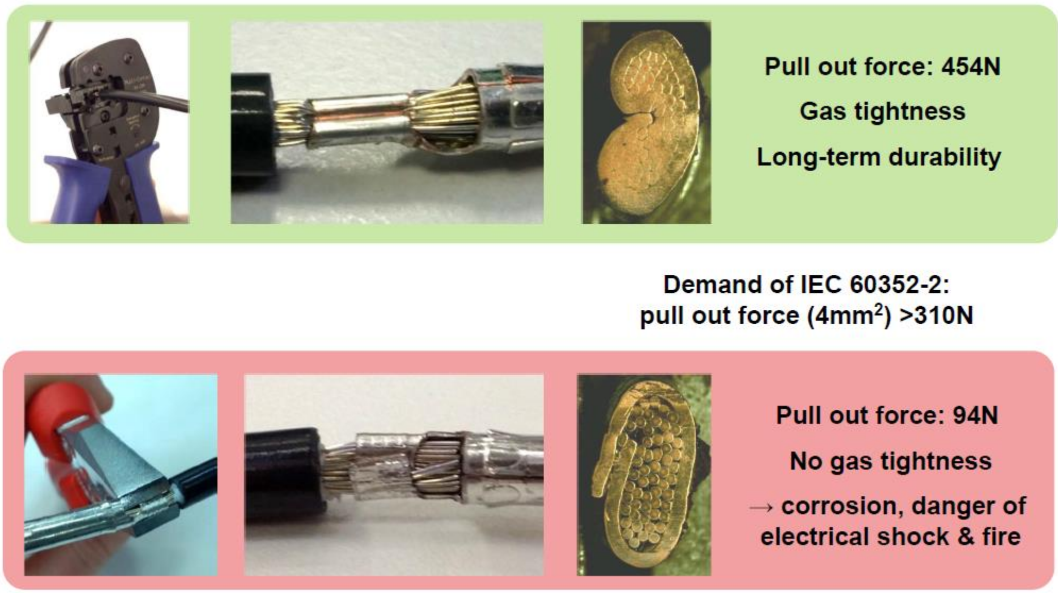

Figure 5: Comparison between connection with correct and incorrect crimping pliers (Berginski, 2013)

3.2 Mismatching DC-Connectors

When talking about problems with DC-connectors, the term "*mismatching*" (or cross mating) often appears. Mismatching means that a connection between a male and female connector is made with DC-connectors from different manufacturers.

Next to the incorrect mounting of connectors, mismatching is regarded as one of the main error sources which makes DC-connectors more likely to ignite. But why is it such a big risk? The following reasons have been previously identified:

- Different materials are used by different manufacturers. This can lead to the following:
  - Chemical incompatibility resulting in corrosion → ingress of water
  - Different thermal expansion behaviour resulting in arcing
- Small differences in the design and the mechanical tolerances of the connectors, which can result in arcing

Multi-Contact (now Stäubli Electrical Connectors AG), manufacturer of the most commonly used DC-connector the MC4, performed lab tests on cross-mated connectors. The results showed increased resistance, leading to temperature increases up to 97°C above the ambient temperature (Figure 6), when connecting MC4 connectors with other connectors from different manufacturers.

Although many manufacturers of DC-connectors often claim their products to be "MC4 compatible", no international standards exist to test intermateability, as highlighted by UL (IAEI NEWS, 2016). Also, Stäubli itself does not recognize any third-party product to be compatible with MC4 connectors. In the IEC TR 63225: 2019, p.4, it is stated that "*this claim of compatibility is potentially misleading as it suggests a safe interoperability of DC connectors from different manufacturers*".

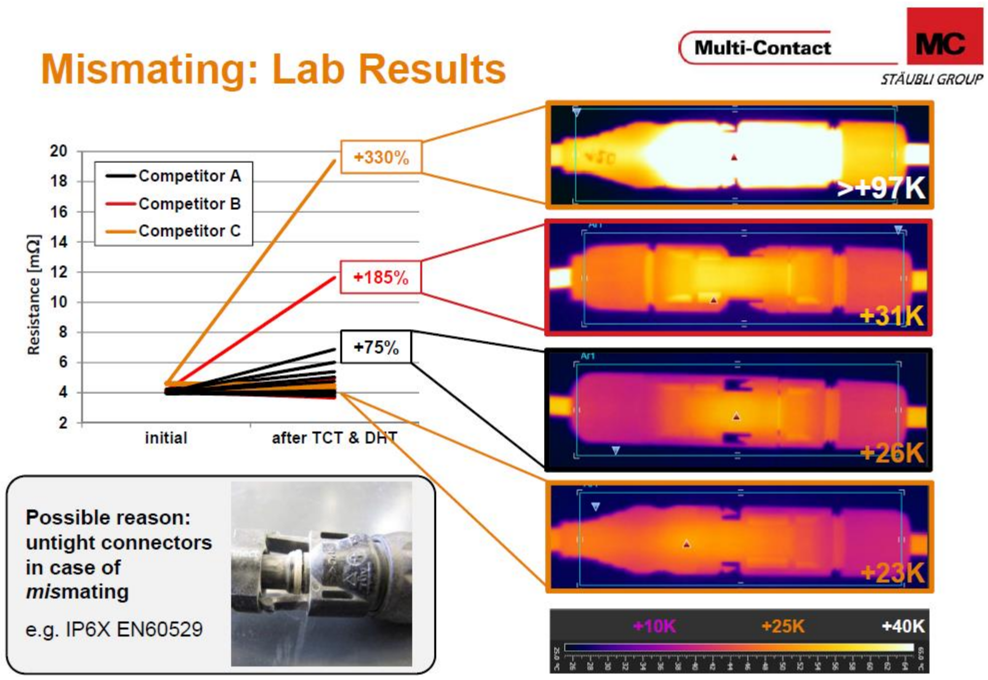

Figure 6: Accelerated degradation tests results for mismatched combinations of connectors between Stäubli MC4 and connectors from different manufacturers (Berginski, 2013)

The IEC 60364-7-712:2017, section 712.526.1 – Electrical connections, declares that "*Male and female connectors mated together shall be of the same type from the same manufacturer i.e. a male connector from one manufacturer and a female connector from another manufacturer or vice versa shall not be used to make a connection*". Other important national institutes also agree that the mismatching of DC-connectors is a major cause of accidental fires, e.g. VDE DKE. In an announcement by VDE DKE, it is clearly stated that male and female connectors from different manufacturers are not allowed to be connected (VDE DKE, 2018).

Despite the clear statements and regulations, the problem of mismatching still persists, and often mismatched connections are made at the outer connection points of the strings. This commonly happens because installers, especially when connecting the different strings together, or strings to the inverter, have to use longer cables with possibly a different connector installed. In such situations, in order not to void the module´s warranty by cutting off the DC-connector from the module cables, installers are usually forced to install DC-connectors from different manufacturers.

To address these issues, the IEC is currently discussing long-term measures, aimed to develop a common interface standard, as well as temporary ones (IEC TR 63225:2019). The latter includes prohibiting the use of the term "MC4 compatible", as well as the requirement for module manufacturers to specify the connectors or provide spare connectors of the same type and brand, or otherwise they should allow connectors to be cut without invalidating the module´s warranty.

3.3 Power Optimizers – a Dangerous Safety Measure

It is obvious that DC-connectors are needed to interconnect PV-modules, as well as to connect the resulting strings to the inverter, but every additional connection on the roof increases the probability that a fire may occur. Therefore, when designing a PV-array, the minimization of the number of contact points on the roof should be an important premise in order to increase the safety of PV-systems.

As noted by TÜV Rheinland and Fraunhofer ISE (Sepanski et al. 2015, p. 204): "Each additional component poses the risk of additional contact points and other sources of faults. A 'sleek' system with as few components as possible has the advantage of having fewer points where damage could occur to the system".

The investigations which followed the US fires at Walmart mentioned above have revealed that before these events occurred, the installation company owning the PV plants was replacing faulty connectors and optimizers across the country (Lopez, Business Insider 2019). It is clear that, although the connectors have been regarded as the main cause of fire, add-on MLPE (module-level power electronics) devices might still have a negative impact on safety, especially when it comes to determining the number of connectors on the roof.

Non-integrated power electronics, such as classical DC power optimizers, used to fulfil the module-level shutdown requirements in the U.S. (NEC 2017), require the use of additional DC-connectors on each module. This means that the number of connection points on the roof will be significantly increased. For illustrative

purposes, Figure 7 shows a 6-kW PV system with two possible configurations: one with retrofit DC optimizers and the other with a string inverter.
As shown, the additional devices installed on the PV modules within the DC circuit roughly triples the number of contact points on the roof: 61 connectors with optimizers, compared to 21 connectors for a string inverter system. The situation would not change significantly by using one optimizer every 2 or 4 modules (51 and 46 connectors, respectively), however the optimization would be less effective.

Therefore it is far more likely that installation errors and mismatching of DC connectors to occur, which in turn increases the risk of fire. The latter is further increased as some optimizer manufacturers provide their products with very few options of DC-connectors brands (ECN TNO 2019), which poses a higher risk of mismatching during installation.
Furthermore, having power electronic devices for every module adds a considerable number of components to the roof, which will increase the system complexity and the product failure rate. This means that maintenance will be required more often, which results in increased costs and in higher risks for the service personnel due

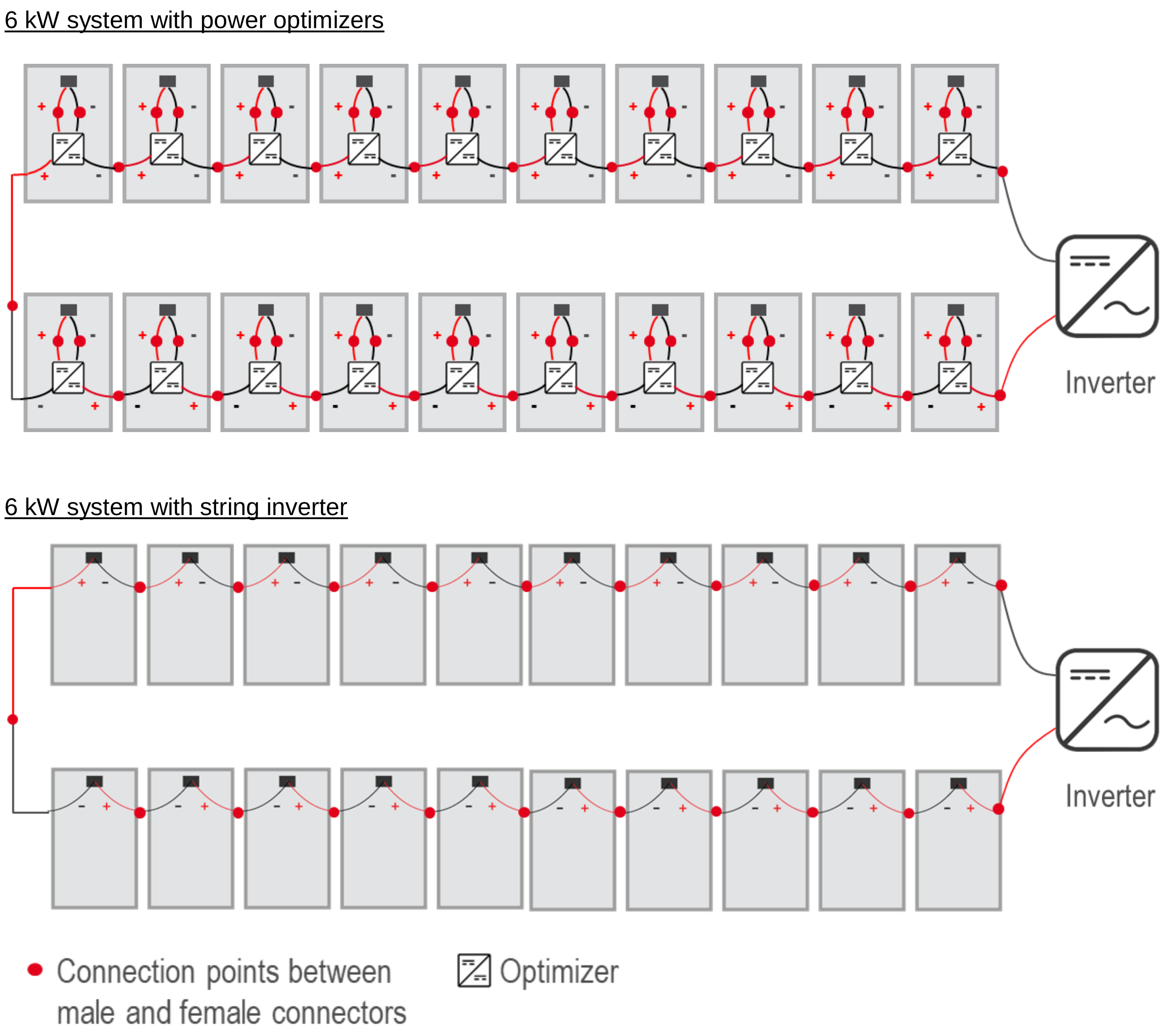

Figure 7: Comparison of two 6-kW system configurations with add-on optimizers (top) and string inverter (bottom).

to the additional time spent on the roof (falls are the main cause of death in construction workplaces), as highlighted in Elsevier SciTech Connect (Plante, 2018).

4 PV FIRE – TACKLING THE IMPROBABLE

A joint industry study carried out in Germany (Fraunhofer ISE 2017) concluded that photovoltaic systems do not pose any special threat to firefighters, as long as the firefighters comply with the safety clearances. PV systems can be handled in the same way as any other electrically live equipment. According to the results of research activities carried out by BRE National Solar Centre (BRE 2017b), disconnection switches in the DC circuit of PV systems are still perceived as an unproven technology. This technology has yet to prove its reliability for the whole lifetime of a PV system. The installation of such devices may give the firefighters a false sense of security, which may lead to accidents, injuries, or worse if a damaged PV array is still energised. The same conclusion can also be drawn with regard to module level shutdown.

In fact, in a study from TÜV Rheinland and Fraunhofer ISE (Sepanski et. al. 2015; p. 206), it is assumed that an installation of a DC-switch, or "fireman's switch", increases the risk of a fire. The main reason for a fire in a PV system are serial arcs, and most fire incidents caused by PV systems can be assigned to installation faults (BRE 2017c; p. 10).

The recommendations for German firefighters and emergency responders during incidents that risk coming into contact with electrically live parts also apply for PV systems. The German Standard *VDE 0132:2008, Firefighting and assistance in or near electric installations*, states safety distances for emergency responders which should help them avoid the risk of electrocution when close to live parts while extinguishing a fire, including a potentially damaged PV system. For a PV system with maximum voltages of up to 1.5 kV, the VDE 0132:2008 recommends a minimal safety distance of 1 m if extinguishing the fire with a water spray jet and 5 m if using a full water jet.
In Austria for example, similar safety distances are recommended in official training documents for firefighters. The Austrian ÖNORM F2190 defines the following safety distances between live parts up to 1 kV and the mouthpiece of a standardized CM-multi-purpose branch pipe, which is commonly used:

- spray jet 1 m
- full water jet 5 m

To demonstrate that the safety distance is sufficient to protect emergency personnel against electrocution, a test was carried out in Germany (Fire Retardants Online 2011 cited in BRE 2017b) where a PV array was set on fire to discover the impact of the fire on the PV modules. Next to other findings, results showed that if the minimum safety distances recommended in the German firefighter guidelines are kept during extinguishing the fire, no unusual hazards arise.

5 RECOMMENDATIONS & CONCLUSION

The most important finding, that has been stated by Fraunhofer ISE (Fraunhofer ISE 2017), TÜV Rheinland (Sepanski et. al. 2017), BRE National Solar Centre (BRE 2017a), and the International Energy Agency Photovoltaic Power Systems Program (IEA PVPS 2017) is that components of PV systems are tested according to very stringent safety and reliability test protocols during the manufacturing process and fulfill electrical safety requirements of various national and international codes and standards. If properly installed, they pose no health, safety, or environmental risks under normal operating conditions. Among the limited number of PV fires reported to date, the main cause of fire was found to be related to DC connectors, mostly due to faulty installation of connectors as well as connector mismatching.

5.1 Recommendations to Reduce the Risk of Fire

To further increase the safety of a PV system and to minimise the risk of fire, we recommend the following:

- **Simplified system design with minimum number of DC-connectors:** The complexity of a PV system should be minimised in order to limit the number of components and the number of contact points. This measure directly decreases the risk of fire due to the reduced likelihood of mismatching as well as installation errors of DC-connectors.
- **Professional installation and commissioning:** Especially IEC 62446-1: "Photovoltaic (PV) systems - Requirements for testing, documentation and maintenance – Part 1: Grid connected systems – Documentation, commissioning tests and inspection" lists points that should be checked before commissioning a PV system.
- **Periodical maintenance of the PV system:** Especially IEC 62446-2: "Photovoltaic (PV) systems - Requirements for testing, documentation and maintenance – Part 2: Grid connected systems – Maintenance of PV systems" gives a good guidance regarding such a periodical maintenance.
- **Daily, automated insulation monitoring:** Before the inverter starts operating, it checks the insulation. If a fault is detected, the inverter will not start operating and give a notification that something is not in order. This monitoring is also performed during operation. If an irregularity is detected during operation, the inverter switches off and gives an error code.

  Monitoring of PV system: A PV system including a Fronius inverter can be monitored all the time by the system´s owner by registering the PV system in Fronius Solar.web. Through the monitoring system, an overview of the system performance is provided, and warnings are sent in case something is wrong. Power decreases independent of weather conditions can be a sign of a fault in the system, which could potentially lead to a fire.

As mentioned in Chapter 1.3, taking appropriate measures to minimise the risk of fire directly reduces the risk for emergency responders, because no fire means no risks for emergency responders like firefighters. Therefore, before taking measures to reduce the risk for emergency responders, the priority should always be to reduce the risk of fire in the first place. Once the risk of fire is minimized, additional safety measures for firefighters can then be introduced, the most important of which are discussed in the next chapter.

5.2 Additional Measures to Reduce the Risk for Firefighters

Derived from the findings of Chapter 4, the following measures are recommended to reduce risks:

- **Clear and easily visible signage or labelling of PV components:** Time is an important factor when tackling a fire! When arriving at the scene of a fire, it is inevitable for the task force commander to ascertain the situation and derive the operational strategy to tackle the fire and handle other tasks such as rescuing people. Based on the fact that every task force commander is trained to perform a dynamic risk assessment of the potential dangers on site before giving orders to their team, it is crucial that they are aware whether a PV system is on site or not.
- **Maintain safety distance:** A deviation from the safety distances described in Chapter 3 could lead to hazards for rescue personnel. It is highly recommended to comply with those safety distances in order to avoid injuries or electrocution.
- **DC disconnector:** This device ensures that the inverter is disconnected from the modules in the event of an incident.

Most crucial for the safety of firefighters is periodical education and training. Knowing what to do in a certain situation saves time, material goods and, most importantly, lives. Firefighters are well trained and dealing with electrical systems is nothing new for them. As long as they are aware of the risks on site, they are able to deal with them.

The easiest way to prove that the concerns and rumours identified in Chapter 1.1 are false is by comparing them to the findings of the recent studies:

- **Firefighters do not extinguish a fire in buildings with a rooftop PV system:** *"Based on investigations to date, all of the claims stating that the fire brigade could not extinguish a house fire due to the PV system have been found to be false." (Fraunhofer ISE 2017)*
- **A rooftop PV system massively increases the risk of fire:** *"To date, 0.006 % of all PV plants in Germany have caused a fire resulting in serious damage!"; "PV plants do not present a greater fire risk than any other technical facilities." (Fraunhofer ISE 2017)*
- **A rooftop PV system massively increases the risk of injuries during an emergency for firefighters:** *"In Germany, no firefighter has to date been injured by PV power while putting out a fire."* (Fraunhofer ISE 2017)
- **Module level shutdown reduces the risk of fire:** *"…disconnection switches are still an unproven technology which have yet to prove their reliability for the whole lifetime of the PV system, and installing them might give firefighters a false sense of security." (BRE 2017b)*
- **It is not possible to extinguish a fire caused by PV:** "*As with every electrical installation, depending on the type of electric arc it is also possible to extinguish a fire using water from a distance of one to five meters." (Fraunhofer ISE 2017)*

/ **A rooftop PV system greatly increases the possibility that a building gets struck by lightning:** *"If a PV system is installed on a building, this does not increase the possibility that the building will be hit by lightning, given that the PV-system does not significantly protrude beyond the building." (BDSW 2008)*

Based on the results of recent publications from well-known experts in the PV research and industry sector, the identified rumours are clearly not facts but fiction.

5.3 The Embedded Safety of Fronius Products

Fronius takes safety very seriously, and although PV is a very safe technology, continuously trying to improve the already high safety level of its products is one of Fronius's top priorities. The following figures highlight the areas Fronius is focusing on:

Fronius is focusing on reducing the risk of fire, which directly influences the risk for emergency responders and is therefore the most sustainable and beneficial approach.
As shown in Chapters 2 and 3, installation failures are the most common reasons for fire incidents. The most effective measure for improving the safety of PV systems is professional training for installers, which ensures a high installation quality and reduces the risk for fire as well as the risk for firefighters.

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