Thermal exposure to roofs from fires involving photovoltaic panels

Fire engineering research services

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Executive summary

This literature review, commissioned by the Building Safety Regulator and prepared by OFR Consultants, investigates the fire safety implications of photovoltaic panels (PV) installed on rooftops. It consolidates experimental findings, international incident data, and current regulatory frameworks to evaluate the extent to which rooftop PV systems alter fire dynamics and pose additional risks to roof constructions and firefighting operations.

The rapid expansion of PV technology, driven by global decarbonisation efforts, has introduced new fire hazards in the built environment. Two primary forms of PV systems are addressed: building-applied photovoltaic systems (BAPV), which are retrofitted to existing roofs, and building-integrated photovoltaic systems (BIPV), which are building elements that also function as PVs. This review places particular emphasis on BAPV systems due to their increasing prevalence and complex interactions with existing roof constructions.

Key fire safety concerns include the alteration of thermal exposure patterns caused by PV modules, which often create semi-enclosed spaces between the roof and the PV panel, that trap heat and redirect flames towards the roof surface. Experimental studies consistently show increased heat fluxes of up to 50 kW/m² beneath PV arrays, significantly exceeding the 12.5 kW/m² considered in standard test methods such as BS EN 13501-5. These conditions have been shown to facilitate fire spread across roofing membranes previously deemed adequate under current classifications.

The review identifies a range of parameters that influence fire behaviour in PV roof systems, including gap height between the PV panel and roof, panel inclination and geometry, roof construction materials (e.g., insulation and membrane types), array configuration and array spacing.

Experimental research demonstrates the existence of critical thresholds, such as gap height, beyond which flame spread is either minimised or exacerbated. For instance, flame spread may accelerate by a factor of 38 when gap height falls below critical limits due to enhanced heat retention and re-radiation, when compared to a scenario without a PV. These findings of changes in fire dynamics are consistent across multiple independent studies conducted at medium and large scales.

The review also highlights that existing classification tests and building guidance in England (e.g. Approved Document B and CEN/TS 1187 Test 4) do not fully capture the unique fire dynamics introduced by PV arrays. These tests assess roof coverings in isolation and do not account for the modified fire scenarios introduced by PV system geometry, installation techniques, or system-wide behaviour.

In addition to technical and experimental insights, the review draws attention to practical challenges for emergency responders. PV systems operating on direct current (DC), introduce persistent electrical hazards even after power disconnection. The presence of PV arrays can also obstruct firefighting access to the fire under the PV panel, impair ventilation systems, and if combined with battery storage, pose chemical or explosion hazards.

Several recommendations are proposed in light of the findings: Use of non-combustible roof coverings beneath PV arrays, fire-resistant construction from the exterior inward to mitigate roof penetration, design guidance for PV layout, including minimum gap heights and array segmentation to limit flame spread and ensure compatibility with compartmentation and smoke venting and development of new test methods that accurately reflect the modified fire conditions created by PV systems.

Given the current regulatory and technical gaps, the review concludes that enhanced design practices and possible updates to testing and classification systems warrant further research to ensure rooftop PV installations do not compromise fire safety in the built environment. This should then lead to changes in technical policy.

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1. INTRODUCTION

1.1 Appointment

OFR Consultants Ltd have been engaged by the Building Safety Regulator (BSR), who are part of the Health and Safety Executive (HSE), to deliver the 'Real Fires' project in support of fire safety technical policy. The Technical Policy Division of the Department for Levelling Up, Housing and Communities (DLUHC, now the Ministry for Housing Communities and Local Government, MHCLG, and whose responsibilities are now held by the BSR), originally commissioned this project on the 22nd of October 2021. The duration of the contract still stands from its initial award by DLUHC, running from the original commissioning date for four years.

As part of this project, the contract makes allowance for ad-hoc research to be undertaken to support fire safety technical policy on matters that emerge through dialogue with the industry or through observations of real fires. Through this mechanism, OFR has been asked to conduct a comprehensive literature review on the thermal exposure to roofs from fires involving photovoltaic (PV) panels. This review will focus on previously conducted research addressing ignition and fire hazards from photovoltaic panels installed on buildings. Additionally, the scope includes a critical review of existing roof classifications included in design guidance, like Approved Document B (ADB) (1,2). This exercise will involve comparing these classifications with the current applications of PV systems on roofs to assess their validity and representativeness in addressing the identified hazards.

1.2 Background

At COP26 in 2021, António Guterres stated: *"We know what must be done. Keeping the 1.5°C goal within reach means reducing emissions globally by 45 per cent by 2030.* (3)*"* This urgent call for action has driven a rapid expansion of renewable energy sources, PV technology. The increasing adoption of PV installations has been facilitated by significant cost reductions, making solar energy more accessible and encouraging its integration into the built environment. One prominent application is the use of unexploited roofs for building-applied photovoltaic (BAPV) systems (Figure 1), which provide efficient means of utilising elevated surfaces for solar energy production (4).

Figure 1. Example of a building-applied photovoltaic system (BAPV) on a flat roof construction

Alongside this growth, an increasing number of fire incidents related to PV systems have been reported, raising concerns about their fire safety implications. A fault tree analysis of all available data on PV-related fires has estimated an annual frequency of 28.9 fires per gigawatt of installed capacity. This highlights the need for a comprehensive understanding of fire hazards associated with PV technology, particularly in the context of rooftop installations (4).

Photovoltaic systems can be installed in a wide range of sizes and configurations, from small domestic installations generating a few kilowatts (kW) to large commercial systems producing power in the megawatt

(MW) range. Within the built environment, a distinction is made between BAPV systems (Figure 1), which are retrofitted onto existing structures and present unique fire safety challenges due to their placement and interaction with the existing building design (4), and building-integrated photovoltaic (BIPV) systems, where the PV components form part of the building envelope (e.g. the façade elements as per Figure 2).

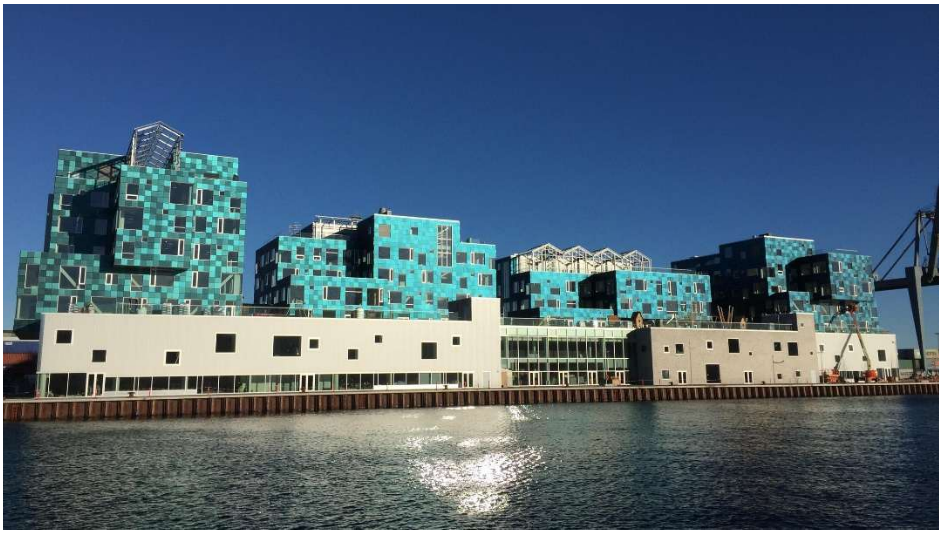

Figure 2. Example of building-integrated photovoltaic panels (BIPV) of the Compehaguen Internation School

Since BIPV systems serve a dual function as both photovoltaic panels and building elements (e.g. façade panels), in most cases, they must meet the fire safety requirements applicable to the corresponding building component. As a result, they undergo the same standard reaction-to-fire tests as conventional building elements that serve the same function but do not generate electricity.

In contrast, BAPV systems modify the roof construction geometry due to the introduction of PV panels as physical objects. Roof structures are typically designed to mitigate flame spread over the surface and the penetration of fire from outside-to-in. However, the presence of PV panels can alter roof performance in a fire scenario. This change in geometry creates a semi-enclosure that may facilitate fire spread and/or roof penetration, potentially breaching fundamental fire safety objectives . Specifically, the ability of the building envelope to contain fire and prevent external flame propagation could be compromised, increasing the likelihood of fire spreading from one compartment to another (4).

Another critical factor contributing to fire risk in PV systems is the nature of their electrical components. Electrical faults are a well-documented source of ignition in fire incidents, and the introduction of large direct current (DC) systems adds further complexity. Unlike alternating current (AC) systems, which are commonly used in household electrical networks, DC arcs formed by system malfunctions are continuous and do not extinguish naturally with current alternation. This increases the likelihood of sustained electrical faults leading to fire ignition (5,6).

2. Problem Identification

Based on fundamental fire dynamics, underlying physics, and previous experimental studies on similar fire spread scenarios, it becomes apparent that PV systems on roofs may introduce new fire hazards. The presence of PV modules alters heat transfer mechanisms and modifies fire growth patterns, exposing the roof construction to a novel heat load and complicating firefighting operations. Understanding these changes is crucial to ensuring fire safety in buildings with rooftop solar installations.

2.1 Changes in fire dynamics

The addition of PV systems to roofs influences fire behaviour by trapping heat closer to the surface, increasing temperatures and heat fluxes, and potentially accelerating fire spread. Without PV modules, fires on rooftops may remain contained; however, with their presence, the energy released is retained near the roof surface, creating conditions for faster fire propagation. Additionally, PV modules, typically composed of glass, aluminium frames, and polymeric materials, can introduce an extra fuel load to the roof structure. Another concern is fire spread through roof skylights located beneath a PV system and over fire barriers, particularly if these elements are not sufficiently elevated above the roof level (7).

There are various factors that influence the fire dynamics of a roof equipped with a PV system. Research has shown that evaluating the fire hazard of a PV installation by considering only the individual materials and components of the system can lead to inaccurate conclusions (4,7–11). Instead, it has been found that the PV installation should be regarded as an integrated system, which includes the panels, mounting structures, and the roof construction, in order to accurately assess the fire hazard. Consequently, the insurance industry is now developing system-wide approval protocols for these installations.

The inclusion of a PV system on a roof changes the fire scenario significantly. In the event of a fire, flames may be deflected beneath the panels, causing a substantial amount of heat to be redirected back towards the roofing covering. This can result in flame spread in areas where it would otherwise be minimal, assuming the roofing covering meets the required fire classification. Figures 5 and 6 adapted from (4,7) illustrate the difference between scenarios with and without panels installed:

Without overlying panel: No (or negligible) flame spread beyond the ignition source (here a wood crib, which was used in the experiments that confirmed this fire development).

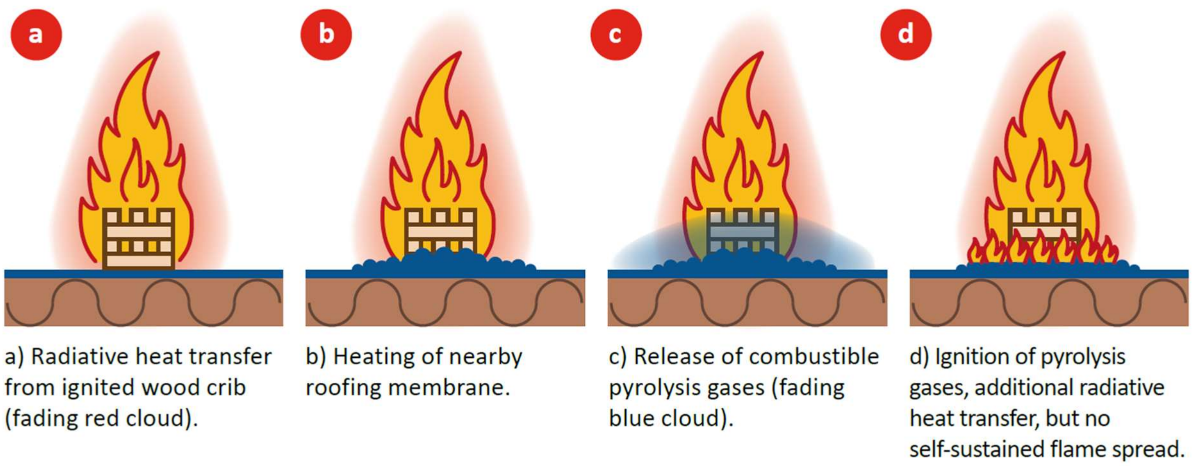

Figure 3. Illustration of the ignition process for a wood crib on a roof construction (blue: roof covering, brown: insulation) (4,7).

With overlying panel: Significant flame spread underneath the PV panel.

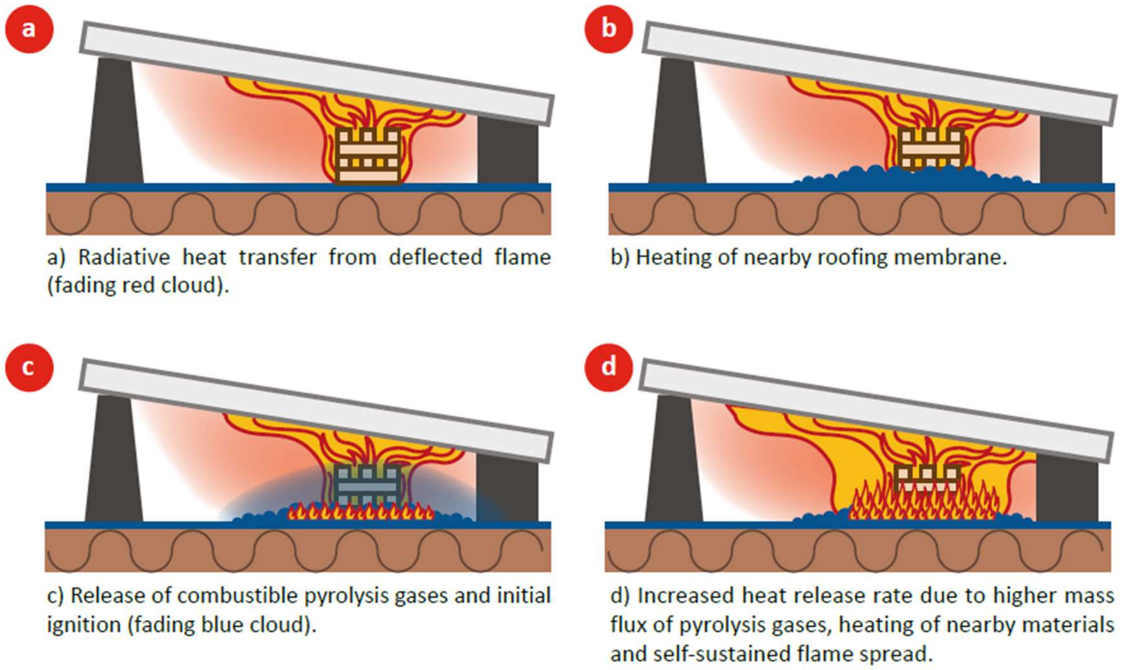

Figure 4. Illustration of the ignition and flame spread process for a wood crib below a PV module (inclined grey rectangle) on a roof construction (blue: roof covering, brown: insulation) (4,7).

Several parameters play a crucial role in governing the fire dynamics in a PV-related fire, including the gap height between the panels and the roof, the inclination of the panels, the roof construction, which involves the type of covering and insulation materials used, and the array configuration, such as the size of the array and the spacing between individual arrays.

2.2 Thermal exposure to the roof construction

The interaction between PV systems and different roof constructions significantly affects fire development. Various roofing materials, including membranes and insulation, have different degrees of combustibility. Some insulation materials and membranes can contribute to fire growth, particularly in concealed spaces between the PV panels and the roof. The combination of certain PV installations with specific roofing materials can heighten fire risks, making careful selection and evaluation essential (7).

It is important to differentiate between retrofits and new builds. Retrofitting an existing roof to accommodate rooftop solar panels is the more common approach, largely because repurposing existing roofs and buildings is seen as a more sustainable option compared to constructing new ones (7).

Figure 5, extracted from (7), outlines two typical configurations for the two main categories of roof construction.

- For retrofitted roofs, studies have demonstrated that a typical setup with expanded polystyrene (EPS) and a membrane over the roof base requires a mitigation layer to prevent the involvement of EPS, which is critical to avoid a large fire. According to most insurance standards, this mitigation layer generally consists of a non-combustible insulation layer topped with a new roof covering. As the overall system's behaviour is crucial for fire safety in PV installations, it is recommended that the performance of the mitigation layer be validated through reliable experimental data or statistics (7).

- For new roofs, it is advisable to avoid using highly combustible insulation materials like EPS above the roof base. Instead, a less flammable alternative, such as non-combustible insulation, should be used, followed by a roof covering. This recommendation is based on publicly available test results, which indicate that the spread of fire across roofs facilitated by PV modules is influenced by the type of roof covering (7).

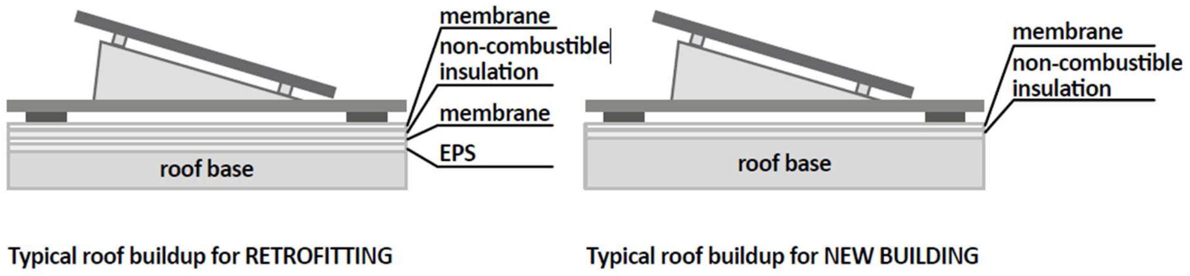

Figure 5. Sketches of typical roofs buildups for retrofits (left) and new builds (right)(7).

2.3 Challenges for firefighting operations

The presence of PV modules complicates firefighting operations by obstructing access to the roof, limiting vertical ventilation, and introducing additional electrical hazards. During daylight hours, a significant portion of the electrical system may remain energised, creating a constant hazard for emergency responders. Unlike traditional systems where electrical isolation may be possible, firefighters are unable to rely on the certainty of deactivating the incoming electrical supply, thus increasing the hazard during a fire (7). Furthermore, designers should be aware that the positioning of PV panels, whether in new builds or retrofits, must consider fire safety provisions such as Automatic Opening Vents (AOVs) or similar systems. Improper placement of PV panels could obstruct these safety features, potentially compromising their effectiveness in controlling fire spread and ensuring safe ventilation.

In addition to electrical hazards, PV systems, particularly those equipped with battery storage, can present chemical and explosion hazards. As part of a growing trend in energy technology, battery storage is increasingly used to balance electrical loads on grids by storing excess energy generated during periods of high solar output. This stored energy can then be used when generation is low, or demand is high. Large battery banks used for this purpose may contain hazardous substances such as sulfuric acid and hydrogen fluoride, which can pose severe health risks during a fire. Additionally, hydrogen gas accumulation within battery storage areas increases the potential for explosions, highlighting the need for enhanced safety considerations in the design and installation of PV systems (7).

3. Review of existing research

Generally, two types of research approaches are associated with PV installations and fire. The first type of research is conducted by mainly electrotechnical engineers who focus on reducing the likelihood of ignition caused by components related to the PV system, summarised in section 3.1. Secondly, the consequences of ignition are the focus of fire safety engineers and the main research finding up to date are summarised in section 3.2.

3.1 Factors affecting ignition

Understanding the causes of ignitions associated with photovoltaic systems is essential for assessing their fire safety performance. Various studies from different countries have attempted to quantify the frequency and causes of PV-related fires. However, due to inconsistencies in data collection methods, precise assessments remain challenging. Despite these limitations, existing datasets provide valuable insights into common ignition sources and trends.

3.1.1 Most relevant data sets on PV-related fires

Several national and international studies have documented fire incidents involving PV systems. In Germany, an analysis of reports from fire departments, insurance companies, and online media identified 430 PV-related fires by early 2013, of which 210 were directly attributed to the PV system itself (8). Italy reported a significantly higher number of PV-related fires, with estimates ranging between 1,800 and 2,200 incidents from 2011 to 2014 (9,12). Similarly, in Australia, where nearly one in four households had PV panels installed by 2020, PV-related fire incidents increased fivefold between 2016 and 2021 in New South Wales (13). Data from the Netherlands indicate a smaller but notable number of incidents, with 29 PV-related fires reported in both 2018 and 2019, rising to 39 in 2020 (14). Meanwhile, the United States classifies PV-related fires under general fire categories, limiting the availability of specific statistics. However, studies have attempted to estimate the impact of PV systems on fire behaviour (4).

3.1.2 Most commonly identified ignition sources

From an electrical engineering perspective, PV system failures can be categorised into different types, with direct current (DC) arcing being a primary concern. Research has identified two main types of arc faults:

1. Parallel arcing: This typically results from cable degradation, aging, or mechanical damage. It is relatively easier to detect and occurs when damaged cables allow unintended electrical connections (15).
2. Series arcing: This occurs due to poor electrical connections between two terminals, which can result from moisture ingress, improper wiring, or poor installation. Series arcing is more complex to identify because it often develops slowly over time as increased resistance generates heat, leading to thermal stress and eventual arc formation (16).

The severity of a DC arc depends on its location within the system, as the arc power is determined by both current and voltage. Experimental studies have demonstrated that DC arcs of 200 W and 800 W can burn through PV cables in 7 seconds and 1.7 seconds, respectively, with arc temperatures reaching 6000K (17).

Additionally, analysis of German fire incident data from 2012 revealed that PV-related failures occur most frequently during the first year after installation, between March and August, likely correlating with increased solar exposure and between 12:00 and 15:00, when sunlight intensity is at its peak (8).

These patterns suggest that seasonal and operational factors significantly influence the likelihood of ignition in PV systems.

3.1.3 Frequency analysis outcomes

Steemann has conducted one of the most complete frequency analyses of PV-related fires (4). A frequency analysis of PV-related fires across five countries estimated an annual rate of 29.3 fires per gigawatt of installed capacity. However, inconsistencies in data collection suggest that this figure may overestimate fire occurrences compared to media-reported incidents (4).

Steemann's findings indicate that many PV-related fires result from unknown system components or ignition sources unrelated to the PV system itself. Among identifiable causes, DC switches, inverters, and connectors—all susceptible to poor installation—were the most frequently implicated. This suggests that while improving PV system reliability could reduce ignitions, focusing solely on ignition prevention may not be sufficient. Instead, strategies should emphasise fire containment and minimizing fire spread to enhance overall fire safety in PV installations.

Clean Energy Associates (CEA) has conducted over 600 safety audits of rooftop PV installations, revealing that 97 percent of the systems presented safety issues linked to ignition hazards. A detailed breakdown of their findings is illustrated in the accompanying bar chart in Figure 6. Given these findings, it can be inferred that the occurrence of at least one ignition event over the lifespan of a PV installation is highly likely. These results align with observations from FM Global, which has reported ongoing instances of ignition and fires even in buildings that adhere to their safety recommendations (7).

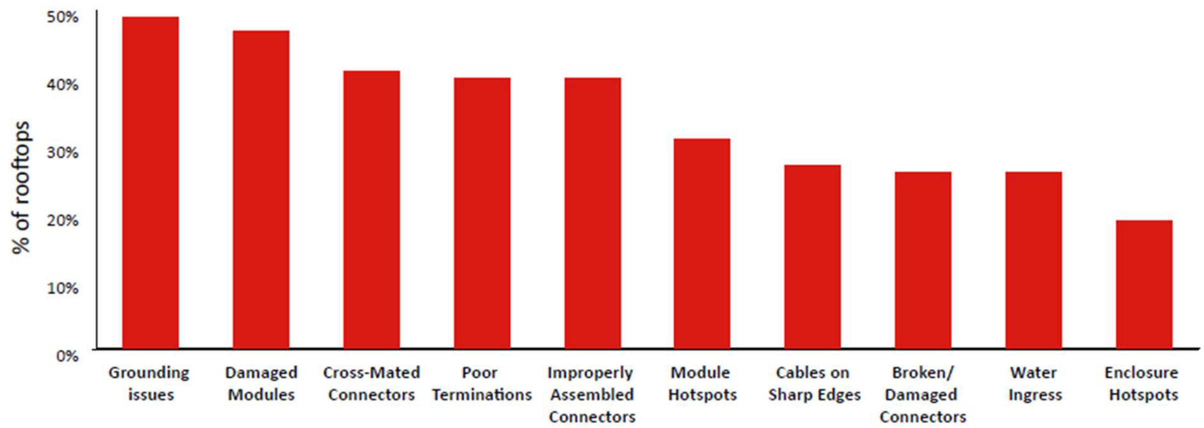

Figure 6. Overview of the failures reported by the Clean Energy Associates (CEA) (https://www.cea3.com/ceablog/top-10-pv-rooftop-safety-risks) in 2023.

To improve risk assessment accuracy, researchers recommend enhancing fire incident reporting by including standardised questions in post-fire reports, specifically identifying whether a PV system was involved and, if so, the specific cause. Implementing a more systematic and consistent data collection approach will allow for a better understanding of fire risks and the development of more effective mitigation strategies.

3.2 Fire Safety Hazards

The field of fire safety associated with PVs has been the subject of extensive research over the past decades. The first section summarises the research conducted up to 2018, and it is followed by two summaries of the work of Steemann, Jomaas and Stølen, whose research represents the most extensive and comprehensive investigations into the fire risks of PV systems to date. Their studies provide critical insights, robust experimental data, and in-depth analyses that have significantly shaped the field.

3.2.1 Research conducted before 2018

In 2010, Backstrom et al. investigated whether the introduction of one or more photovoltaic (PV) modules affected compliance with the UL 790 test standard for roofing products in the United States. To assess maximum flame spread distances, six tests were performed using gap heights ranging from 30.5 cm to 71 cm. These experiments were carried out on an inclined surface, incorporating four different gap heights, four types of roof coverings, and both PV modules and surrogate panels. As a result, the effects of individual parameters could not be isolated, making it impossible to determine their specific influence. Nevertheless, the results indicated that fire conditions consistently worsened with the presence of PV panels, and the researchers recommended offsetting the PV modules from the roof surface to a degree where their impact on fire dynamics becomes negligible. All large-scale tests conducted by Backstrom et al. utilised a line gas burner positioned at the edge of the test setup, simulating an external ignition scenario. This scenario, however, could have been mitigated by the presence of a wind deflector (18–20).

Despinasse and Krueger conducted experiments in which a gas burner was applied to either the front or back of a PV module. Based on their findings, they proposed a new test method in which failure was defined by burn-through of the PV module occurring within 15 minutes (10).

Cancelliere and Liciotti investigated the fire reaction of four different photovoltaic (PV) module back sheets using a single-point flame source test (UNI 8457) and the UNI 9174 standard. The materials were then classified according to the applicable fire classification system. They also adapted the test setup proposed in CLC/TR 50670 by incorporating a 0.375 m² sheet of roofing membrane and placing it inside the test chamber of the single burning item (SBI) test (EN 13823) to evaluate PV modules as construction products. However, since the setup involved both the PV module and the roofing membrane, the method assessed the fire performance of a combined system rather than the PV module alone. This approach also introduced variables such as gap height and module inclination. Consequently, the proposed test method was considered a pass/fail test rather than an evaluation of the PV module as an isolated component (21).

Yang et al. assessed the thermal stability of photovoltaic (PV) module back sheets using a cone calorimeter, determining a critical heat flux of 26 kW/m² for PV modules containing a single PV cell. Their findings were later supported by Ju et al., who identified critical heat flux values of 18.8 kW/m² for the back side (0.5 mm Tedlar, a polyvinyl fluoride material) and 20.8 kW/m² for the front side (2.5 mm glass) of a polycrystalline silicon module (22).

Three studies conducted between 2010 and 2018 utilised a similar experimental setup initially introduced by Steemann, Merci and Jomaas (11), which was later refined by Ju et al. (23) and further developed by Tang et al. (24). This setup, illustrated in Figure 7, measured the heat flux received at various distances from a central gas burner. Steeman et al. highlighted the significance of the deflected flame from the burner, which contributed to an increased heat flux directed toward the surface below. Building upon this, Ju et al. modified the setup by inclining the upper surface ($0° \leq \theta \leq 30°$), varying the gap height ($5\ cm \leq h \leq 15\ cm$), and measuring heat flux, as well as the upstream and downstream flame extension. They also proposed a model to quantify re-radiation as a function of a non-dimensional local flame thickness. Their findings showed that a reduction in gap height led to an increase in heat flux toward the lower surface (representing the roof surface). However, increasing the inclination effectively raised the gap height at the location of the gas burner (H), making direct comparisons across similar gap heights difficult (23).

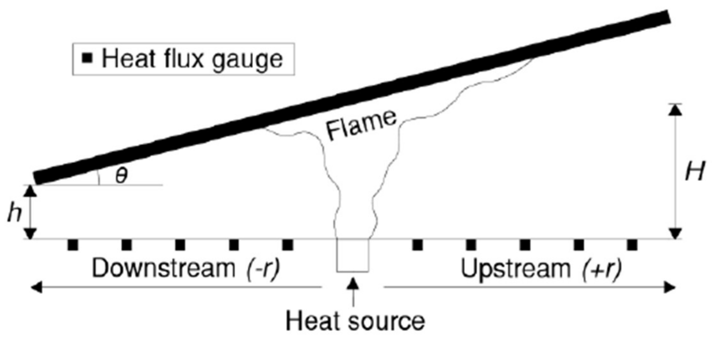

Figure 7. setup showing that the flame is deflected significantly upwards underneath the PV panel.

Despite slight variations in the results of the three experimental series, the observed trends remained consistent and well-defined. The presence of a horizontal barrier, whether non-combustible or a PV module, significantly increased the radiative heat flux toward the surface beneath it, as illustrated in Figure 8. Even at lower heat release rates, the damaged length of the bottom surface exceeded the critical length as determined for a BROOF(t2)[1] (EN 13501-5 (25)) compliant roofing membrane (26).

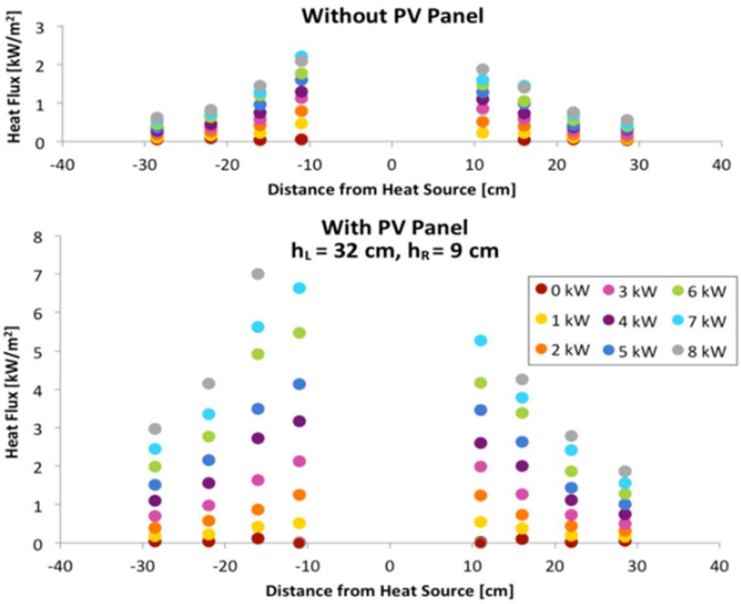

Figure 8. The Heat Flux received as a function of distance to, and HRR from, the heat source. Each colored dot defines a HRR and the gas burner is placed at the distance of 0 cm from the heat source, extracted from (25).

Moreover, observations indicated the absence of self-sustained flame spread along the PV module back sheet. These findings suggested that while the PV module itself may not serve as a direct fuel source, it can act as a facilitator or catalyst in fire propagation (23,26). This aligns with the heat of combustion values for fluoropolymer back sheets, which Tewarson determined to range between 4.1 kJ/g and 5.4 kJ/g (27).

3.2.2 Steemann et al.

As highlighted in the introduction, Steemann and Jomaas have carried out one of the most significant research studies on the fire safety of PV systems. In 2018, they published in (11) the outcome of a large-scale experimental campaign that assessed the fire dynamics and flame spread behaviour associated with PV panel installations on flat roof constructions. The study aimed to characterise the fire hazards introduced by these systems, particularly in the context of retrofitting PV panels onto warehouse roofs, where expanded polystyrene (EPS) insulation and polyvinyl chloride-based roofing membranes (classified as BROOF(t2)) are commonly used. To

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[1] The BROOF(t2) classification is the result of the CEN/TS 1187 testing methods, specifically Test Method 2. This test exposes a sloped roof setup, at 30 degrees, to burning brands combined with wind, evaluating how the roof covering reacts under thermal attack.

The roof covering is tested in combination with one of several standard substrates, which include non-fire-retardant wood particle board, expanded polystyrene, fibre-reinforced calcium silicate board, or mineral wool.

The test is carried out using a wooden crib as the ignition source, and wind is applied at two speeds: 2 m/s and 4 m/s. Each wind speed is tested in three separate trials to ensure consistency and repeatability.

During the 15-minute test (or until the fire is extinguished or reaches the top of the test body), the spread and intensity of fire damage are monitored. After the test, the damaged length of both the roof covering and the substrate is measured. To achieve a BROOF(t2) classification, the mean damaged length must be less than 0.55 m, and the maximum damaged length must be less than 0.80 m, under both wind conditions.

If these criteria are not met or the performance is not evaluated, the product may be classified as FROOF(t2), indicating no determined fire performance under this test method.

evaluate potential fire mitigation strategies, the experiments incorporated two protective layers: 30 mm mineral wool and 40 mm polyisocyanurate (PIR) insulation.

Each experiment involved a mock-up roof structure with six PV panels arranged over an area measuring 6.0 m in length, with widths of either 2.4 m or 4.8 m (Figure 9 and Figure 10). A small wood crib, placed beneath the PV panels, served as the ignition source. The fire ignited the roofing membrane within 7 to 8 minutes, leading to flame spread beneath all six PV panels, covering an area of approximately 5.1 m × 2.0 m. However, fire propagation beyond the PV array was not observed, regardless of wind conditions.

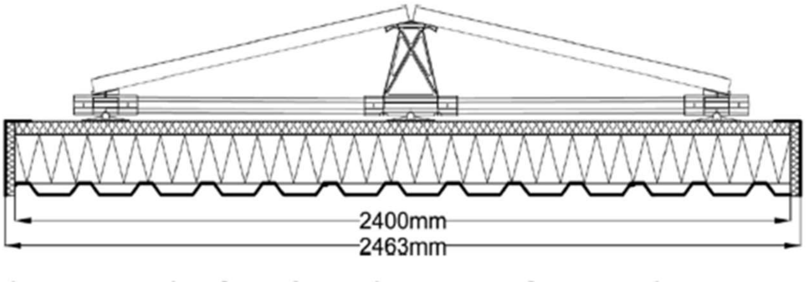


Figure 9. Sectional cut of experiments T1 and T2. Experiments T3 and T4 were identical except from the width of the roof construction.

Figure 10. Experiment T3. The whole area underneath the PV array was affected by the fire.

The results demonstrated that the altered geometry by the presence of the PV module, rather than the fire load of the PV panels or external wind effects, played a dominant role in fire spread. The PV panels facilitated heat retention and re-radiation, contributing to fire propagation over the roof covering. Maximum temperatures of 175°C and 243°C were recorded beneath the PIR insulation and mineral wool, respectively—well below the piloted ignition threshold for EPS. Despite this, EPS ignition occurred in both tests involving PIR insulation after approximately one hour due to thermal degradation and loss of mechanical integrity. In contrast, mineral wool remained stable throughout the experiments, preventing EPS ignition.

These experiments confirmed that an initial small fire beneath a PV installation can escalate into a hazardous scenario due to altered fire dynamics. If combustible construction materials become involved, in conjunction with the effect of a PV array, they can act as fuel loads, amplifying the severity of the fire.

Steemann continued with this research line during his PhD (4) under the supervision of Jomaas and finished in 2022. He conducted three different experimental campaigns to study the effect of different parameters separately that affect fire spread in BAPVs, which are discussed below.

3.2.2.1 Flame spread on PMMA in horizontal semi-enclosures.

To assess the impact of geometry on fire behaviour, this first experimental campaign explored how variations in the gap height between the upper and lower surfaces of a semi-enclosure influenced fire dynamics. The roof construction was replaced with polymethyl methacrylate (PMMA), a well-documented reference material extensively studied in fire research (28,29).

A total of 50 fire tests were conducted, including 11 baseline experiments (i.e. without a PV panel) to validate the setup and ensure reliability. In all tests, PMMA was used as the lower surface to maintain consistency and minimise material variability. Additionally, in most of the remaining experiments, a stainless-steel board was used in place of a PV module to further simplify the material complexity and isolate key fire behaviour parameters.

A picture of the experimental setup is illustrated in Figure 11.

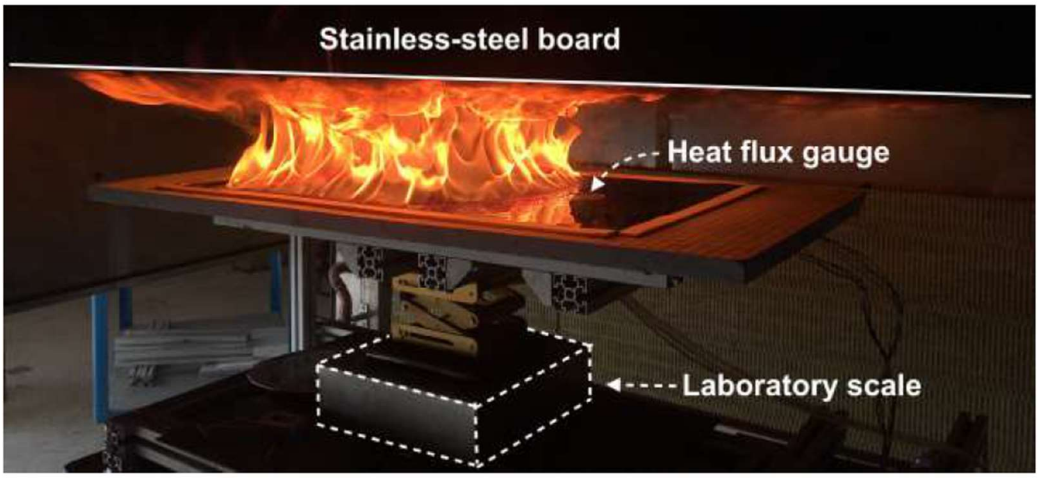


Figure 11. Image from an experiment in progress. The location of the stainless-steel board, heat flux gauge, and laboratory scale are highlighted. Sample width of 400 mm.

Figure 12 presents the experimental temperature, flame front location, and heat flux data of an exemplary experiment conducted for this campaign. It is interesting to observe a slow fire growth until approximately second 1200, when the fire starts growing exponentially, triggering incident heat fluxes to the 'roof' surface of almost 50 kW/m^2 and temperatures of approximately 900 °C.

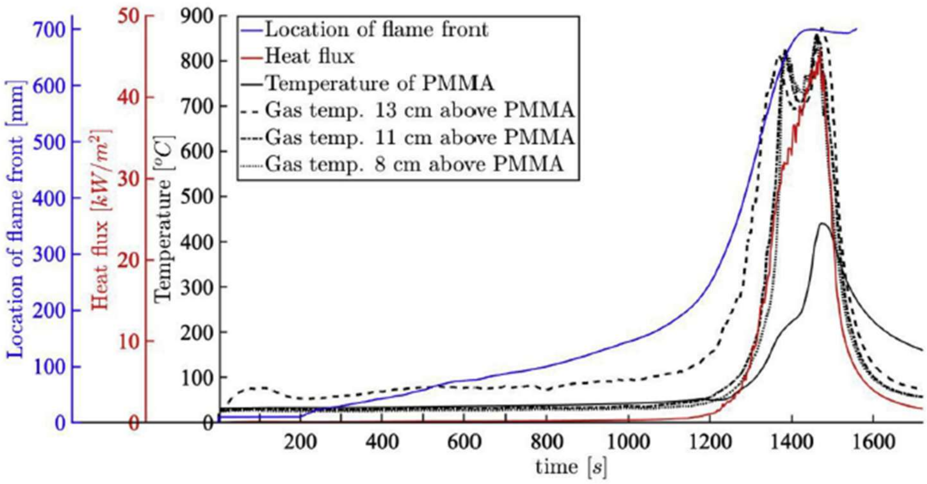


Figure 12. Sample width: 30 cm. Gap height: 15 cm. Plot of flame front location, heat flux, temperature 5 cm in front of the HFG, and gap temperature at three heights above the HFG.

These experiments revealed a critical gap distance, beyond which the flame spread rate increased significantly. Above this critical gap height, the flame spread rate remained constant and slow. However, when the gap height fell below the critical threshold, the flame height began to grow steadily until it exceeded the gap, causing the flame to be deflected below the panel. This deflection resulted in a sharp increase in combined heat flux towards the pre-heating zone, accelerating the flame front by up to 38 times compared to baseline experiments without a panel. This behaviour can be easily observed in the experimental data presented in Figure 13, which presents the location of the flame front over time for different gap heights between the PMMA sample and horizontal boards.

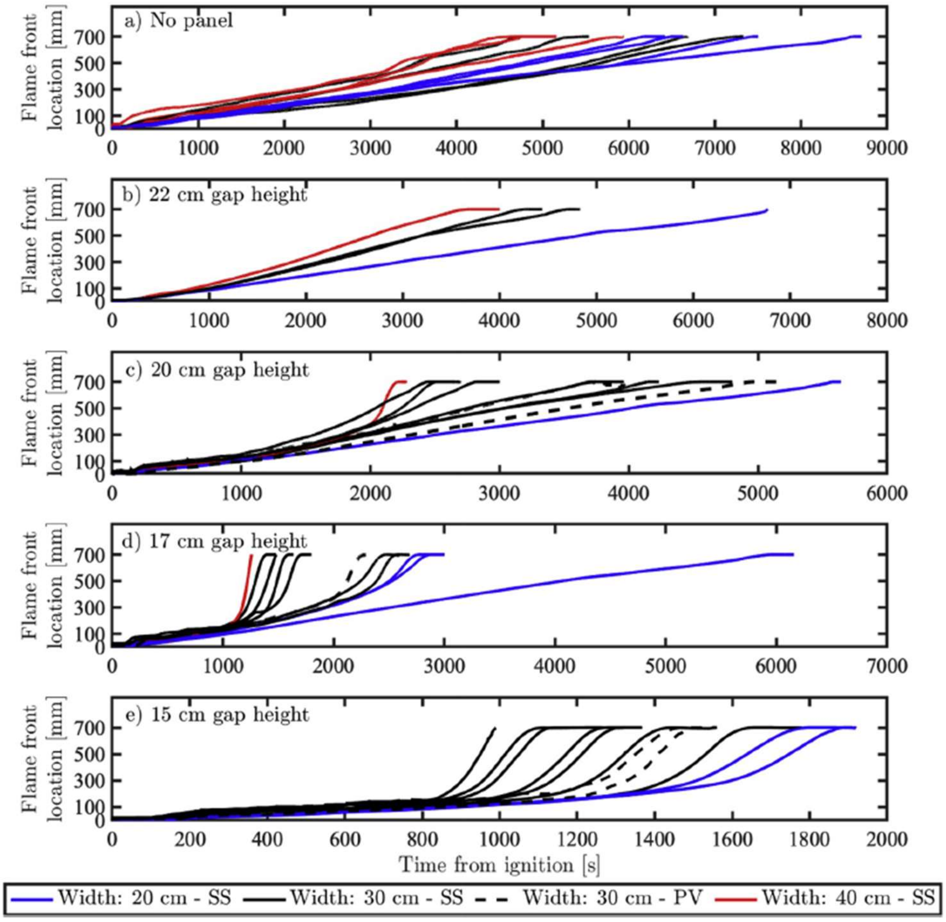


Figure 13. Location of flame front as a function of time from ignition at various gap heights.

The transition from a low, constant flame spread rate to a rapid acceleration occurred over a narrow range of gap heights, with differences as small as 2–3 cm, emphasising the crucial role gap height plays in PV installations. Additionally, the width of the sample influenced the critical gap height, with larger sample widths correlating to a lower critical gap height.

The experiments also showed no enhanced flame spread attributable to the combustible components of the PV modules compared to similar tests conducted with a non-combustible black stainless-steel plate. This finding aligns with earlier studies on new and used PV modules (30), where the increased heat flux was attributed to re-radiation from the PV module, not to the marginally higher fuel load of new modules versus used ones.

3.2.2.2 Flame spread on roof construction mock-up in semi-enclosure.

In this experimental campaign, Steemann conducted 24 experiments to investigate how key parameters influence flame spread length and rate in the semi-enclosed space between a PV system and a roof mock-up, as well as the heat transfer and temperature development within the roof structure. The course of an exemplary experiment is illustrated by a series of photographs in Figure 14. The experimental setup represented a flat roof with a building-applied PV system and an ignition source consisting of a pine wood crib, allowing for good repeatability (Figure 15). our main parameters were analysed: the type of panel (either PV modules or a stainless-steel board), the gap height between the panel and the roof, the inclination of the panel, and the composition of the underlying roof construction. A PVC-based roofing membrane (B_{ROOF}(t4)) was used in all tests, with three different roof constructions beneath it. Initially, a calcium silicate board was tested, followed by two variations aimed at reducing heat transfer towards an expanded polystyrene (EPS) layer, representing a worst-case scenario. These variations included 60 mm of PIR insulation and 50 mm of mineral wool.

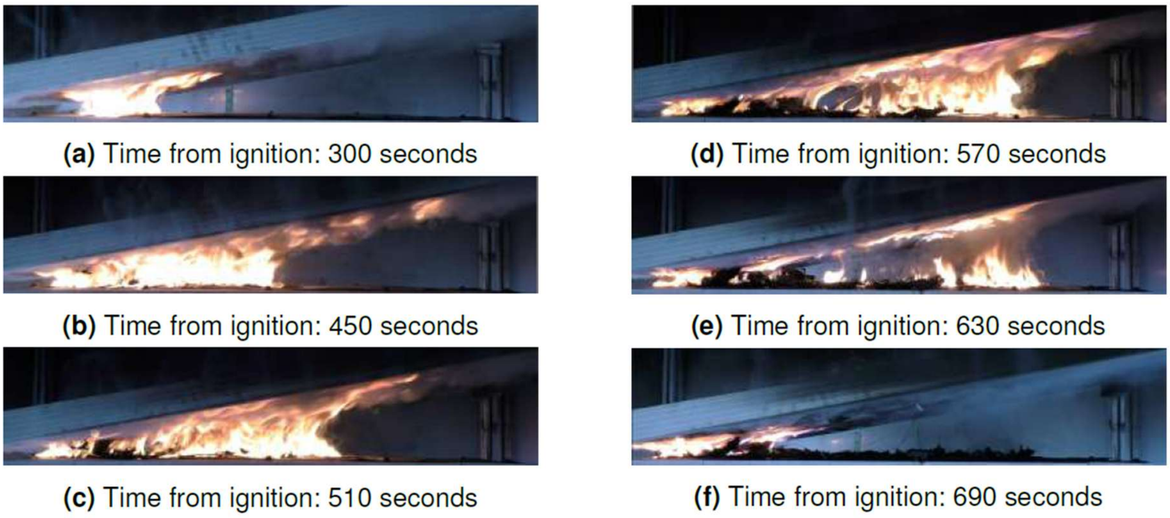


Figure 14. Flame spread on roof construction mock-up with mineral wool below the roofing membrane, a gap height of 8 cm, and an inclination of 10°, from (4).

Figure 15. Top view of the mock-up roof construction before ignition of the wood crib. The wood cribs were made of pine sticks with a length of 81 mm and a squared cross-section with a side length of 9 mm, from (4).

For experiments involving horizontal panels, no self-sustained flame spread occurred at a 12 cm gap height. However, reducing the gap to 11 cm allowed flames to propagate across the entire roofing membrane.

When using the stainless-steel board instead of PV modules, a further reduction to a 10 cm gap was required to achieve consistent flame spread (Figure 16). The polymer back sheet of the PV modules only ignited at points of direct flame impingement, meaning it did not significantly contribute to the fuel load or influence flame spread in the semi-enclosure. Instead, the lower critical gap height observed for PV modules was attributed to their aluminium frame, which blocked the upward movement of buoyancy-driven combustion products. This obstruction created a continuous hot smoke layer underneath the panel, which had two notable effects: (i) enhanced preheating along the entire roof mock-up, promoting flame spread, and (ii) reduced effective gap height, leading to increased airflow velocity and, consequently a decrease in flame spread rate.

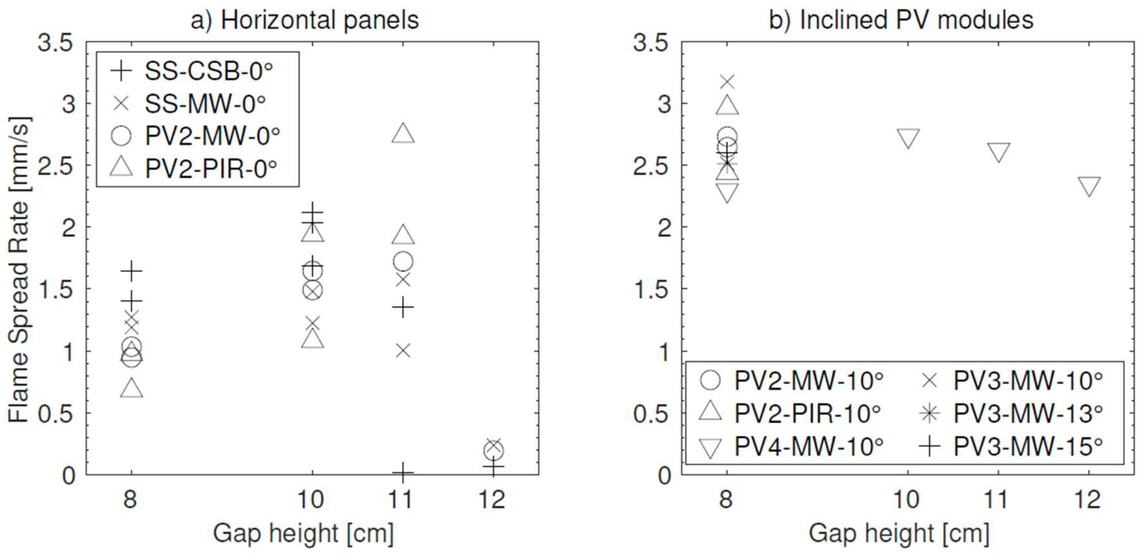


Figure 16. Flame spread rate (FSR) as a function of gap height, panel type (Stainless-steel board (SS) or PV module (PV2, PV3, or PV4)), or insulation material (Calcium silica board (CSB), mineral wool (MW), or PIR insulation) for experiments conducted below: a) Horizontal panels, or b) Inclined PV modules, extracted from (4).

When the PV modules were inclined, the effects of the hot smoke layer were no longer observed, as the inclination allowed combustion products to escape upwards along the back of the modules. However, this inclination also intensified heat flux beneath the elevated section of the module, leading to self-sustained flame spread in all cases. Based on these observations, it was concluded that the critical gap height for inclined PV modules exceeded 12 cm, as per Figure 16 (b)

It is important to note that the critical gap heights determined in this experimental campaign are specific to the tested system and its components. Nonetheless, a key finding of this study is that the experiments demonstrated that PV modules facilitate flame spread on a roofing membrane that complies with current European fire classification standards (EN 13501-5). This underscores a major concern: integrating a PV system into a flat roof may undermine fundamental fire safety strategies. Specifically, the presence of PV panels can transform a compliant roof system into one that enables flame spread, as the re-radiation from deflected flames beneath the modules causes an initially small fire to escalate, potentially spreading along the building envelope, which could lead to circumvention of compartmentation.

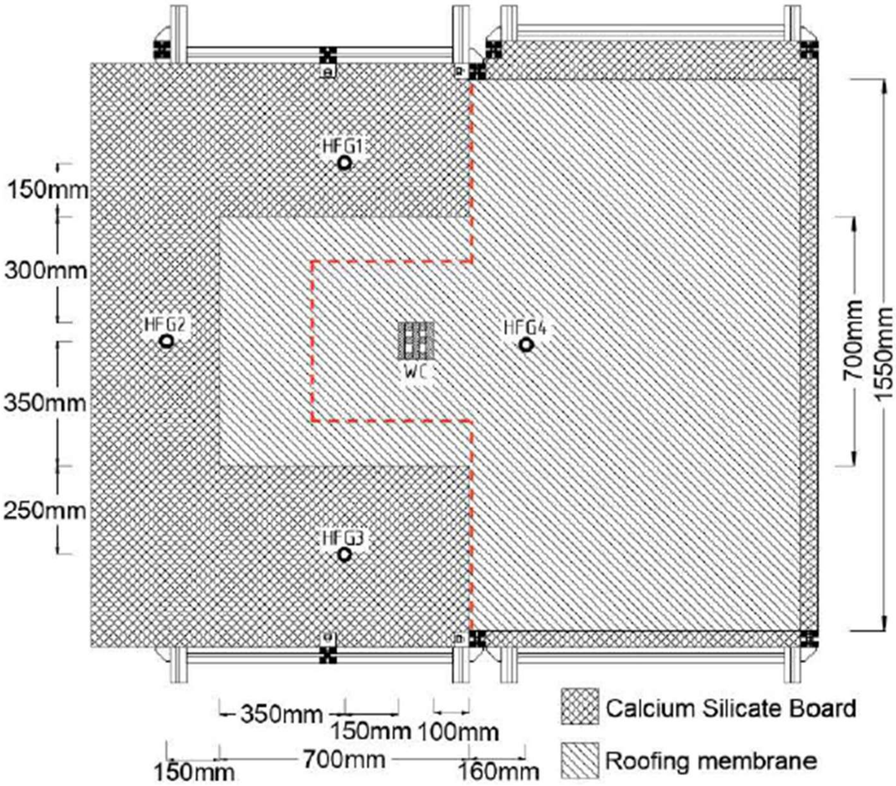
3.2.2.3 Medium-scale experiments with adjacent roof.

With the larger experimental setup presented in Figure 17, twelve experiments were conducted to quantify the HRR from a fire within a semi-enclosed space formed by a horizontal roofing membrane and an inclined PV module. Heat fluxes were measured both inside and outside the semi-enclosure. In each test, two square sections of roofing membrane, with side lengths of 45 cm and 70 cm, were ignited within the enclosure. The experimental outcomes were influenced by several variables, including the membrane size, the condition of the PV module (new or used), the hood extraction flow rate (which could be interpreted as wind conditions), and the positioning of the wood crib used for ignition.

A key finding was that the extraction flow rate played a decisive role in the fire behaviour. If the initial flow was too high, the pyrolysis gases from the heated roofing membrane became diluted, preventing ignition. Conversely, maintaining a constant extraction flow resulted in a slower flame spread rate compared to scenarios where the flow was increased to an optimal level at the right moment.

Overall, the twelve experiments underscored the sensitivity of the fire dynamics within the semi-enclosure, where even minor variations, such as a slightly higher heat flux due to burning roofing membrane in one of the experiments, led to significantly different outcomes in otherwise nearly identical tests.

(a) Side view of the experimental set-up with the roofing membrane and wood crib installed in correspondence with the sectional top view in Figure 3.10b.



(b) Sectional top view of the experimental set-up with a 700 mm times 700 mm (shaded), or 450 mm times 450 mm (marked with dashed red lines) area of roofing membrane below the PV module and 10 cm displacement of the wood crib from the edge of the PV module similar to the setups C7 to C10 in Table 3.8. **HFG:** Heat Flux Gauge. **WC:** Wood Crib.

Figure 17. Visual overview of the medium-scale experimental set-up used to analyse the influence of flow and heat flux in and outside the semi-enclosure formed by the PV module and the subjacent surface, extracted from (4).

3.2.3 Stølen et al.

Another research centre that has focused on PVs fire safety research is the Norwegian branch of RISE, led by Stølen and his team.

Stølen's team continued conducting similar experiments to Steemann et al. In their research presented in (31) they conducted experiments in small, medium and large-scale, where all consisted of replicating a system of semi-enclosures/cavities created by sloped roof construction and a steel panels above it.

Figure *18* presents three pictures of their largest-scale experiment.

Figure 18. Medium-scale experiments with a wood crib placed on top of a roofing membrane with a steel plate (left) and without a steel plate (left inserted). Large-scale experiment with steel plate on a roof measuring 4.2 × 5.4 m (middle). Fire propagation in large-scale approximately 20 minutes after ignition where the fire has spread up to the top of the roof (red arrow) and down to the lower edge in the flowing melted bitumen roofing membrane (white arrow) (right), extracted from (13).

The roof structure featured a bitumen roofing membrane over a wooden chipboard substrate. To simulate the influence of BAPV modules, steel plates were positioned at varying distances above the roof. The fire development within the gap between the roof and the steel plate was analysed using different wood cribs as ignition sources.

They concluded that the presence of PV modules on a roof classified as B_{ROOF}(t2) enhances fire spread when an ignition source is located beneath the module. The extent of this effect is influenced by both the gap between the module and the roof surface and the size of the ignition source. If the ignition source is sufficiently large, it can trigger a self-sustaining fire that propagates across the roof. The buoyant plume primarily drives fire spread upward along the roof surface, with limited lateral extension. Additionally, burning molten roofing material contributed to fire spread in the downward direction. However, in all experiments, the fire did not penetrate the roof structure, as the 22 mm wood chipboard provided sufficient fire resistance until the roofing membrane was completely consumed.

4. AVAILABLE GUIDELINES IN ENGLAND

In England, there are two guides available that cover the fire safety specifications for the roof structure and roof covering. These guides are Approved Document B (ADB) volume 1 and volume 2 (1,2)

These guides make a distinction for recommendations for roof structures and roof coverings.

4.1.1 Requirements for roof structures

Roof structures that are part of a means of escape and roofs used as a floor will have to be classified to a certain fire resistance rating (REI) to demonstrate adequate structural stability, integrity and insulation (REI rating). The required REI rating are defined in the relevant section of ADB (1,2) and BS 9999:2017 (32), and the classifications are usually obtained via furnace tests according to BS EN 13501-2 (33).

Additionally, roofs with a pitch of more than 70 degrees to the horizontal should be included in the assessment for resisting fire spread from one building to another, meaning that if they do have a lower REI rating than what is required for the external walls of a specific buildings, the roof area will have to account for an 'unprotected area' in the radiation calculations to the relevant boundary.

However, the required REI rating and the standard furnace test described in (33) evaluate the fire resistance of building elements from the inside to the outside. However, PV panels present a situation whereby the thermal attack is from outside-to-in and, thus, not currently addressed in situations where roofs or portions of roofs may need fire resistance.

4.1.2 Requirements for roof coverings

Contrary to the fire assessment of the roof structures, the roof covering materials are assessed according to their behaviour when exposed to an external fire. Roof coverings are classified within the European system as B_{ROOF}(t4), C_{ROOF}(t4), D_{ROOF}(t4), E_{ROOF}(t4) or F_{ROOF}(t4) in accordance with BS EN 13501-5 (33). B_{ROOF}(t4) indicates the highest performance and F_{ROOF}(t4) the lowest. BS EN 13501-5 refers to four separate roof tests performed according to CEN/TS 1187 (34), and the suffix (t4) indicates that Test 4 is to be used.

This test is designed to evaluate the performance of a roof when subjected to thermal attack under conditions involving burning brands, wind, and radiant heat. The assessment focuses on two primary aspects: external fire spread and fire penetration.

The external fire performance of a roof or roof covering encompasses multiple factors, including external and internal fire spread, the extent of damage, fire penetration, and the occurrence of flaming droplets or debris. This performance is influenced not only by the burning behaviour of the exposed roof surface but also by several structural components, such as the type and thickness of insulating layers, vapour barriers, and their supporting elements. Additionally, the method of attachment of these components, whether through adhesives or mechanical fastening, can significantly impact fire performance (34).

To ensure the test specimens accurately represent real-world applications, they must incorporate all relevant construction details, including the substrate and deck, the type, number, and joining methods of all roofing layers (such as insulation and vapour barriers), and the specific methods used for fixing these layers (34).

The test procedure for Test 4 evaluates roof performance through a two-stage approach that simulates fire exposure using burning brands, wind, and supplementary radiant heat. The standard testing pitch is set at 45°, except for specimens representing flat roofs with a pitch of up to 10°, which are tested horizontally. Tests may also be conducted at the intended installation pitch, with the obtained classification applicable only to that specific angle.

The classification parameters for the test are divided into two stages. In Stage 1, a preliminary ignition test using burning brands assesses the duration of flaming, the extent of flame spread, and the time and nature of fire penetration. The burning brand is applied for 1 min starting at the centre of the upper surface of the specimen, without exposure to additional radiant heat (34).

In Stage 2, the surface of the specimen is exposed to the 12.5 kW/m^2 radiant heat, and after 5 mins from the start of the test, the burning brand is applied to the surface of the specimen by moving once up and once down the centre of the specimen at a rate of 0.29 m / 10s. The specimen remains exposed to the radiant panels for 1 hour in total. This stage evaluates the time to fire penetration as well as the occurrence of melting and the production of molten droplets or debris, whether flaming or non-flaming. A test example in action is presented in Figure 19 (34).

Figure 19. CEN/TS 1187 test

Image available at: https://system-labs.co.uk/cen-ts-11872012-test-4-b-roof-t4/

Figure 20 presents the testing rig of the ENV 1187 Test 4 Roofing test, where the test sample is placed in a sample holder which is placed on the specimen cover, and an air seal is created. The specimen cover can be tilted and supported at different angles. The suction box assembly is connected to the specimen cover with a suction hose to simulate the effect of wind.

The radiant panel assembly provides the 'supplementary radiant heat' source directed onto the surface of the test sample with a net heat flux of 12 ±1.5 kW/m^2.

Figure 20 CEN/TS 1187 test setup.

Image available at: https://www.fire-testing.com/roofing-test-with-two-stages-incorporating-burning-brands-wind-and-supplementary-radiant-heat-env-1187-test-4/

After conducting the tests, the specimens are classified according to Table 1.

Table 1, Classes of external fire performance for roofs and roof coverings for Test 4 according to CEN/TS 1187

Roof classification	Classification criteria
BROOF(t4)	• No penetration of roof system within 1 h. • In preliminary test, after withdrawal of the test flame, specimens burn for < 5 min. • In preliminary test, flame spread < 0,38 m across region of burning.
CROOF(t4)	• No penetration of roof system within 30 min. • In preliminary test, after withdrawal of the test flame, specimens burn for < 5 min. • In preliminary test, flame spread < 0,38 m across region of burning.
DROOF(t4)	• Roof system is penetrated within 30 min but is not penetrated in the preliminary test. • In preliminary test, after withdrawal of the test flame, specimens burn for < 5 min. • In preliminary test, flame spread < 0,38 m across region of burning.
EROOF(t4)	• Roof system is penetrated within 30 min but is not penetrated in the preliminary test. • Flame spread is not controlled.
FROOF(t4)	• No performance determined.

Finally, the required roof classification for different building types is specified in Figure 21 and Figure 22 for dwellings and for buildings other than dwellings, respectively. These figures are extracted from ADB (1,2), where the roof classification depends on the minimum separation from the roof, or part of the roof, to the relevant boundary.

In addition, roof covering products (and/or materials) defined in Commission Decision 2000/553/EC of 6 September 2000, implementing Council Directive 89/106/EEC, can be considered to fulfil all the requirements for the performance characteristic 'external fire performance' without the need for testing, provided that any national provisions on the design and execution of works are fulfilled, and can be used without restriction.

Table 12.1 Limitations on roof coverings

Designation[1] of covering of roof or part of roof	Distance from any point on relevant boundary			
	Less than 6m	At least 6m	At least 12m	At least 20m
B_{ROOF}(t4)	●	●	●	●
C_{ROOF}(t4)	○	●	●	●
D_{ROOF}(t4)	○	●(2)(3)	●(2)	●
E_{ROOF}(t4)	○	●(2)(3)	●(2)	●(2)
F_{ROOF}(t4)	○	○	○	●(2)(3)

● Acceptable.
○ Not acceptable.

NOTES:

Separation distances do not apply to the boundary between roofs of a pair of semi-detached dwellinghouses and to enclosed/covered walkways. However, see Diagram 5.2 if the roof passes over the top of a compartment wall.

Polycarbonate and uPVC rooflights that achieve a class C-s3, d2 rating by test may be regarded as having a B_{ROOF}(t4) designation.

1. The designation of external roof surfaces is explained in Appendix B.
2. Not acceptable on any of the following buildings.
   a. Dwellinghouses in terraces of three or more dwellinghouses.
   b. Any other buildings with a cubic capacity of more than 1500m³.
3. Acceptable on buildings not listed in (2) if both of the following apply.
   a. Part of the roof has a maximum area of 3m² and is a minimum of 1500mm from any similar part.
   b. The roof between the parts is covered with a material rated class A2-s3, d2 or better.

Figure 21. Table 12.1 extracted from ADB, volume 1: Dwellings (2).

Table 14.1 Limitations on roof coverings

Designation[1] of covering of roof or part of roof	Distance from any point on relevant boundary			
	Less than 6m	At least 6m	At least 12m	At least 20m
B_{ROOF}(t4)	●	●	●	●
C_{ROOF}(t4)	○	●	●	●
D_{ROOF}(t4)	○	●(2)(3)	●(2)	●
E_{ROOF}(t4)	○	●(2)(3)	●(2)	●(2)
F_{ROOF}(t4)	○	○	○	●(2)(3)

● Acceptable. ○ Not acceptable.

NOTES:

Separation distances do not apply to enclosed/covered walkways. However, see Diagram 8.2 if the roof passes over the top of a compartment wall.

Polycarbonate and uPVC rooflights that achieve a class C-s3, d2 rating by test may be regarded as having a B_{ROOF}(t4) classification.

1. The designation of external roof surfaces is explained in Appendix B
2. Not acceptable on any of the following buildings.
   a. Industrial, storage or other non-residential purpose group (purpose groups 6 and 7) buildings of any size.
   b. Any other buildings with a cubic capacity of more than 1500m³.
3. Acceptable on buildings not listed in (2) if both of the following apply.
   a. Part of the roof has a maximum area of 3m² and is a minimum of 1500mm from any similar part.
   b. The roof between the parts is covered with a material rated class A2-s3, d2 or better.

Figure 22. Table 14.1 Extracted from ADB, volume 2: Buildings other than dwellings (1).

Although this standard test more accurately represents real-world conditions for PV-related fires on roofs by exposing the roofing material to an external fire, it is specifically designed to assess only roofing covering materials when exposed to radiant heat from a fire across a boundary. Consequently, the inclusion of PV panels within this test remains open to interpretation.

5. FINAL DISCUSSION

5.1 Summary of observations

This literature review highlights the complex interplay between PV systems and roof coverings, emphasising the need for a more comprehensive approach to fire safety in PV installations. The interaction between PV panels and roofing materials significantly influences fire behaviour, mainly increasing the incident heat flux to the roof surface and the rate of fire spread. Factors such as panel elevation, inclination, mounting systems, wind, and spacing play a crucial role in defining the fire dynamics.

One of the key insights gained from this study is the identification of a critical gap height between PV modules and roof surfaces, beyond which flame spread damage can be minimised. This presents a potential mitigation strategy for existing and new PV installations. However, this approach must be balanced with structural and environmental considerations, such as wind loads and mechanical stability. While the critical gap height can inform fire-safe designs, it is important to recognise that reported values are case-specific and should not be directly integrated into installation standards without further validation.

Although PV panels contribute to an increased fire spread compared to roofs without PV panels, fire propagation beyond the panel-covered area is generally limited. Both real-world fire incidents and experimental studies indicate that once the fire reaches the uncovered roof surface, its spread tends to cease after a relatively short distance for coverings that are classified to a classification that permits limited fire spread. This suggests that fire safety measures could focus on ensuring adequate separation distances to prevent fire spread across the whole roof and to limit it to only one array.

A critical observation from the regulatory review is that roof classification testing does not address or have the means to consider the unique fire dynamics introduced by PV installations. While material properties are considered in classification standards such BS EN 13501-5, crucial factors like the transformation from an open to a semi-enclosed fire scenario due to PV module geometry remain largely unexamined. The impact of installation parameters, including module inclination, roof slope, and gap height, requires more explicit integration into fire safety standards to ensure realistic assessments of fire behaviour in PV systems. In the absence of this, traditional roof classification methods, i.e., CEN/TS 1187 (test 4), are unlikely to adequately characterise the performance of roofs upon which PVs are installed.

The literature review presented in this report includes experiments that demonstrated higher heat fluxes to the roof coverings when PV panels are present. Experiments showed heat fluxes reaching almost 50 kW/m^2, which is much higher than the prescribed 12.5 kW/m^2 in the current BS EN 13501-5 standard. Experiments were also noted where rapid fire spread was observed for roof coverings classified as B_{ROOF}(t4) where fire spread should have been limited. All these changes in fire behaviour are currently impossible to capture by the testing procedure proposed in BS EN 13501-5.

5.2 Recommendations

In the absence of a test capable of addressing the unique fire characteristics induced by the installation of PV arrays on roofs, focus should be placed on mitigating fire spread and roof penetration. This could be through a combination of:

- Ensuring roof coverings are non-combustible where below PV installations, thus limiting the prospect of fire spread.
- Recommending that construction below the PV arrays achieve an appropriate standard of fire resistance from outside-to-in, thus mitigating the prospect of roof penetration.
- Introducing guidance on the configuration and layout of arrays, e.g., minimum gap heights between the roof covering and PV underside, limiting the size of arrays and ensuring that they are appropriately spaced, that PV arrays do not extend over compartmentation and, thus, mitigating circumvention and that they don't compromise smoke vent outlet performance.

The extent to which all or some of the above recommendations are necessary would require additional research to investigate their efficacy.

The alternative to the above recommendations is to consider the development of a roof test that better represents the fire dynamics induced by the installation of PV arrays.

6. References

1. HM Government. The Building Regulations 2010, Approved Document B (Fire Safety) Volume 2 (2019 edition). 2019.

2. HM Government. The Building Regulations 2010, Approved Document B (Fire Safety) Volume 1 (2019 edition incorporating 2020 and 2022 amendments). 2020.

3. Secretary-General's remarks to Global Climate Action High-Level Event - as delivered [Internet]. Available from: https://www.un.org/sg/en/content/sg/statement/2021-11-11/secretary-generals-remarks-global-climate-action-high-level-event-delivered

4. Kristensen JS. Fire risk associated with photovoltaic installations on flat roof constructions: experimental analysis of fire spread in semi-enclosures [Internet]. The University of Edinburgh; 2023 [cited 2025 Jan 11]. Available from: https://era.ed.ac.uk/handle/1842/40402

5. Beyler CL. Ignition Handbook. Fire Technology. 2004 Jul;40(3):295–6.

6. Drysdale D. An Introduction to Fire Dynamics [Internet]. 1st ed. Wiley; 2011 [cited 2025 Mar 24]. Available from: https://onlinelibrary.wiley.com/doi/book/10.1002/9781119975465

7. ZAG, FRISSBE. Fire Safety Guideline for Building Applied Photovoltaic Systems on Flat Roofs. 2024 May.

8. Annett Sepanski et al. Assessing Fire Risks in Photovoltaic Systems and Developing Safety Concepts for Risk Minimization [Internet]. 2018 Jul. Available from: chrome-extension://efaidnbmnnnibpcajpcglclefindmkaj/https://www.energy.gov/sites/default/files/2018/10/f56/PV%20Fire%20Safety%20Fire%20Guideline_Translation_V04%2020180614_FINAL.pdf

9. Luca Fiorentini, L. Marmo, Vincenzo Puccia, Enrico Danzi. Fires in Photovoltaic Systems: Lessons Learned from Fire Investigations in Italy. SFPE 2015.

10. Despinasse MC, Krueger S. First developments of a new test to evaluate the fire behavior of photovoltaic modules on roofs. Fire Safety Journal. 2015 Jan;71:49–57.

11. Kristensen JS, Jomaas G. Experimental Study of the Fire Behaviour on Flat Roof Constructions with Multiple Photovoltaic (PV) Panels. Fire Technol. 2018 Nov;54(6):1807–28.

12. Piergiacomo Cancelliere, Giovanni Manzini, Michele Mazzaro. A review of the photovoltaic module and panel fire tests. In Naples, Italy; 2017.

13. There are –data missing– solar power fires per year [Internet]. pv magazine. Available from: https://www.pv-magazine.com/2019/08/23/there-are-data-missing-solar-power-fires-per-year/

14. M. Leene, R. van den Dikkenberg,. Vooronderzoek depositie bij branden met zonnepanelen [Internet]. 2020. Available from: https://www.ifv.nl/kennisplein/Documents/ 20201208-IFV-Vooronderzoek-depositie-branden-zonnepanelen.pdf

15. Lu S, Phung BT, Zhang D. A comprehensive review on DC arc faults and their diagnosis methods in photovoltaic systems. Renewable and Sustainable Energy Reviews. 2018 Jun;89:88–98.

16. BRE. Fire and Solar PV Systems – Investigations and Evidence. Report No.: P100874-1004.

17. Hastings JK, Juds MA, Luebke CJ, Pahl B. A study of ignition time for materials exposed to DC arcing in PV systems. In: 2011 37th IEEE Photovoltaic Specialists Conference. 2011. p. 003724–9.

18. UL - Underwriters, Laboratories In./,. Effect of Rack Mounted Photovoltaic Modules on the Flammability of Roofing Assemblies – Demonstration of Mitigation Concepts [Internet]. Report No.: Tech. Rep., 2010. Available from: http://www.solarabcs.org/currentissues/ docs/UL_Report_PV_and_Roof_Flammability_Mitigation_2-10-10.pdf

19. Underwriters Laboratories Inc. Report of Experiments of Minimum Gap and Flashing for Rack Mounted Photovoltaic Modules Phase 4," [Internet]. Report No.: Tech. Rep., 2012. Available from: [Online]. Available: http://www.solarabcs.org/current-issues/docs/UL_Report_Gap_and_ Flashing_Exps_3-29-12.pdf

20. B. Backstrom. Validation of Roof Configuration 2 Experiments Project 9 [Internet]. 2013. Available from: http://www.solarabcs.org/current-issues/docs/Validation_of_Roof_ Configuration_2_Experiments.pdf

21. BSI. BS EN 13823:2002 Reaction to fire tests for building products. Building products excluding floorings exposed to the thermal attack by a single burning item. London: BSI; 2002 p. 98.

22. Ju X, Zhou X, Peng F, Wu Z, Lai D, Hu Y, et al. Correlation analysis of heat flux and fire behaviour and hazards of polycrystalline silicon photovoltaic panels. IOP Conf Ser: Mater Sci Eng. 2017 May;201:012036.

23. Ju X, Zhou X, Gong J, Zhao K, Peng Y, Zhang C, et al. Impact of flat roof–integrated solar photovoltaic installation mode on building fire safety. Fire and Materials. 2019 Dec;43(8):936–48.

24. Tang F, Zhu Y, Chen L, Sun X, McNamee M, Van Hees P, et al. Experimental study and analysis of radiation heat fluxes received by a floor beneath an inclined ceiling. Fire and Materials. 2021 Mar;45(2):205–14.

25. BSI. BS EN 13501-5:2016 Fire classification of construction products and building elements. Classification using data from external fire exposure to roofs tests. London: BSI; 2016 p. 34.

26. Kristensen JS, Merci B, Jomaas G. Fire-induced reradiation underneath photovoltaic arrays on flat roofs. Fire and Materials. 2018 Apr;42(3):316–23.

27. Tewarson A, Chu F, Jiang F. Combustion Of Halogenated Polymers. Fire Saf Sci. 1994;4:563–74.

28. Jiang L, Miller CH, Gollner MJ, Sun JH. Sample width and thickness effects on horizontal flame spread over a thin PMMA surface. Proceedings of the Combustion Institute. 2017;36(2):2987–94.

29. Korobeinichev O, Gonchikzhapov M, Tereshchenko A, Gerasimov I, Shmakov A, Paletsky A, et al. An experimental study of horizontal flame spread over PMMA surface in still air. Combustion and Flame. 2018 Feb;188:388–98.

30. BayWa. Mounting system novotegra 2020 [Internet]. 2021. Available from: https://solar-distribution.baywa-re.lu/fileadmin/Solar_Distribution_Benelux/ 08_Kataloge/2020_EN_Montagesystemkatalog_kompirmiert.pdf

31. Stølen R, Siren Fjærestad J, Fjellgaard Mikalsen R, Jomaas G. Experimental study of fire propagation on sloped roof with building applied photovoltaics. J Phys: Conf Ser. 2024 Nov 1;2885(1):012047.

32. BSI. BS 9999:2017 Fire safety in the design, management and use of buildings. Code of practice. London: BSI; 2017 p. 418.

33. BSI. BS EN 13501-2:2016 Fire classification of construction products and building elements. Classification using data from fire resistance tests, excluding ventilation services. London: BSI; 2016.

34. BSI. DD CEN/TS 1187:2012 Test methods for external fire exposure to roofs. London: BSI; 2012 p. 64.