FIRE SAFETY ASPECTS ASSOCIATED WITH

BUILDING APPLIED PHOTOVOLTAIC SYSTEMS

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CONTENT

REPORT INFORMATION

Client:	EURIMA - European Insulation Manufacturers Association
Adress:	Rue de Deux Églises 29 1000 Brussels Belgium
Author:	Jens Steemann Kristensen, PhD
Contact:	jsk@dbigroup.dk
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1. INTRODUCTION

At the request of the European Insulation Manufacturers Association (EURIMA), the Danish Institute for Fire and Security Technology (DBI) has been commissioned to prepare a report evaluating the fire-related risks associated with building applied photovoltaic (BAPV) systems on flat roof constructions.

When BAPV systems are installed on buildings they represent a hazard since they increase the likelihood of an event that can develop into a competent ignition source. In addition, the consequences are altered by the presence of the PV system which amplify the potential damage to people, environment, and/or economy. The product of the increased likelihood and potential consequences results in a significantly elevated risk. While the risk is difficult to quantify, it can be evaluated qualitatively through case studies, the growing interest of the insurance industry [1], [2], as well as ongoing research. Thus, the objective of the report is not to define the quantitative risk as the public available data for such analysis is too sparse [3], but to define and discuss parameters which affect the risk.

The introduction contains a general definition of the terms risk and fire-related risk of BAPV systems. That is followed by sections describing i) the cause of the fires, ii) the potential consequences of the fires and why they differentiate from an open roof construction and iii) ongoing research on the topic.

1.1. Definition of risk – introduction of the Bow Tie

With risk being defined as the probability of an undesired event multiplied by the consequences [4], the structural basis of the report pivots around the fundamental principles and terminology of a Bow Tie model as defined in *Bow Ties in Risk Management: a Concept Book for Process Safety* [5]. Despite the title of the book, and origin of the risk model being chemical and process safety, the model has gained a wider interest and acceptance within other fields such as the rail, aviation, and finance industry [6], [7].

In general, BAPV systems installed on buildings introduce a hazard by increasing the likelihood of an event that can develop into a competent ignition source. Moreover, the presence of the PV system alters the potential consequences, amplifying the risk of damage to people, the environment, and/or the economy. The combination of heightened likelihood and intensified consequences results in a significantly elevated level of risk.

Essentially, Bow Tie models are visual tools where a *top event* defines loss of control related to a specified *hazard.* The *top event* can be triggered by various *threats* and *reduction barriers* can be used to reduce the probability of leading to the *top event*. The term *top event* originates from the concepts of a fault tree analysis which is a quantitative risk model [8], [9]. If, or when, a *top event* occurs, its *consequences* can range from localized incidents to significant damage to people, the environment, property or business continuity. The outcome of the *top event* relies on the mitigation barriers present and failure of some, or all barriers, can lead to different events where the most severe consequences are defined as *major accident events.* The probability of those events can be quantified in an event tree analysis.

As such, the Bow Tie model can be visualised with the *top event* representing the Bow Tie knot, whereas the sides are composed of respectively the threats (left), and consequences (right), that can lead to, or originate from, the *top event*.

1.2. Risk related to building applied PV systems

To qualitatively assess the fire-related risks associated with the implementation of building applied Photovoltaic (BAPV) systems, the fundamental components of the Bow Tie Analysis are defined and presented in Table 1. These components are subsequently discussed in subsections 1.2.1 to 1.2.5 and further elaborated upon in the following sections.

Table 1 – Components in a basic Bow Tie analysis of associated with the fire-related risk of building applied photovoltaic systems on commercial and industrial buildings with flat roofs. The definitions are based on the terminology in [4].

TERM	DEFINITION	CASE
1: Hazard	An operation, activity or material with the potential to cause harm to people, property, the environment or business or simply, a potential source of harm.	PV system installed on building envelope.
2: Top event	In Bow Tie risk analysis, a central event lying between a threat and a consequence corresponding to the moment when there is a loss of control or loss of containment of the hazard.	Formation of competent ignition source.
3: Threats	A possible initiating event that can result in a loss of control or containment of a hazard (i.e., the top event).	An external ignition source, a compartment fire propagating to the roof, or an event associated with electrotechnical failures of the PV system.
4: Consequences	The undesirable result of a loss event, usually measured in health and safety effects, environmental impacts, loss of property, and business interruption costs.	Consequences if the top event can vary from limited local damage to the major accident events (MAE) defined in 5.
5: MAE	Major accident event (MAE). A hazardous event that results in one or more fatalities or severe injuries; or extensive damage to structure, installation or plant; or large-scale, severe and/or persistent impact on the environment. In Bow Ties MAEs are outcomes of the top event.	MAE 1: Flame spread along the roof. MAE 2: Flame spread into subjacent fire compartment.

1.2.1. The hazard

The introduction of any new technology into the built environment inherently presents a hazard, as the combination of novel or previously unidentified threats and consequences can elevate the overall risk associated with a given property. Typically, such hazards are assessed prior to large-scale implementation. However, rapid technology rollouts, unanticipated usage or installation practices, or the deployment of existing technologies in unfamiliar settings may lead to actual hazards that exceed initially perceived risks.
In the case of building-applied photovoltaic (BAPV) systems, the technology itself is not novel, as photovoltaic cells powered the Vanguard satellite between 1958 and 1964[10].

Nonetheless, the rapid commercialisation and large-scale implementation of PV technology over the past decade has led to the exponential growth illustrated in Figure 1, with approximately 40% of global capacity installed on rooftops [11]. Consequently, the demand for qualified personnel continues to grow, along with the drive to integrate PV systems into the built environment, as mandated by the European Commission's REPowerEU initiative [12]. Given that the expected lifespan of a PV system exceeds 25 years [13], only a limited fraction of global capacity has yet endured long-term service conditions. Therefore, one could argue that a thorough understanding of the potential risks associated with PV implementation should be considered essential.

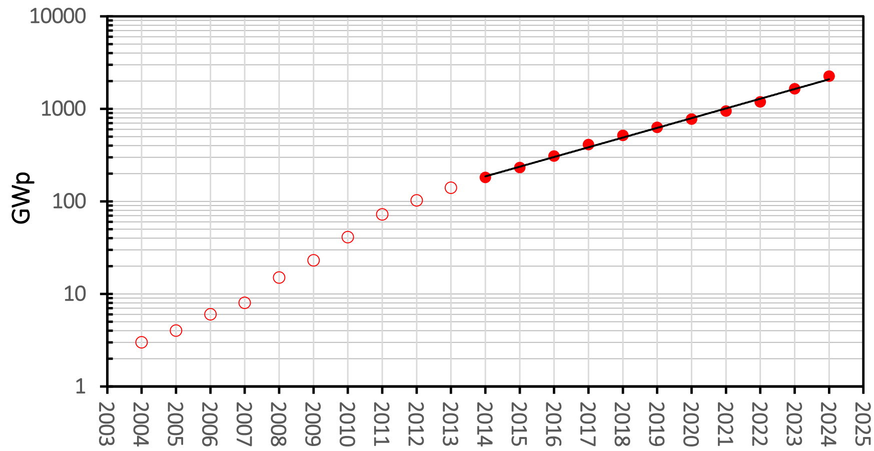

Figure 1 – Global cumulative photovoltaic capacity. Trendline added between 2014 and 2024. Notice: logarithmic y-axis (ordinate). Based on data from: Snapshot of Global PV Markets – 2025 [10]

For BAPV systems, the primary hazard arises from the intersection of two distinct regulatory and standardisation domains: the electrotechnical sector and the building sector. This overlap has led to ambiguities in responsibility, as neither domain alone possesses the comprehensive expertise required to holistically assess the fire-related risks associated with integrating photovoltaic technology into the built environment.

1.2.2. Top Event

When assessing fire-related risk, the presence of an initial ignition source is a prerequisite for the development of any fire. The term *competent ignition source* originates from the field of fire and explosion investigations and is defined by both the National Institute of Standards and Technology (NIST) and the National Fire Protection Association (NFPA) as an "ignition source that has sufficient energy and is capable of transferring that energy to the fuel long enough to raise the fuel to its ignition temperature" [14].

Accordingly, the definition of a competent ignition source may be considered context-dependent, as it is often argued to depend on the characteristics of adjacent materials and the surrounding ambient environment. However, the *top event* is strictly defined as the event that bridges potential threats and consequences, and its impact depends on the extent to which consequences are mitigated. As such, ignition sources represented in most fire safety test methods, such as firebrands, radiation from nearby fires, or flames exiting a subjacent window opening, can all be regarded as competent ignition sources and, therefore, constitute a *top event*. This reason for that is, that the consequences of these ignition sources may be significant if the performance of the roof surface is inadequate, as will be further discussed in Section 1.2.4.

1.2.3. Threats

When testing roof surfaces for buildings without BAPV systems, firebrands, radiation from nearby fires, and flames exiting a subjacent window opening are all highlighted as underlying causes of the *top event*, a competent ignition source, as discussed in section 1.2.2.

In a Bow Tie analysis, prevention barriers are introduced to reduce or eliminate events which, combined and/or as part of an event series can lead to the *top event*. For instance, both the presence of fire brands and radiation requires a nearby fire, which is not predefined and could originate from various scenarios, such as a forest fire, a neighbouring building on fire, or other unforeseen circumstances. Consequently, the probability of the *top event* can be lowered by implementing reduction barriers.

From a fire safety strategy perspective, eliminating threats that can lead to the *top event* should be considered. However, a resilient fire safety strategy requires redundant layers of protection that do not rely on external factors, such as nearby building fires or kitchen mishaps [15], the latter being the leading cause of residential building fires. Thus, a resilient fire safety strategy is often based on the most conservative ignition source that is reasonably likely to occur.

For fires related to BAPV systems, that entails that the introduction of the PV system, does not reduce but solely introduce additional threats in the Bow Tie analysis which can develop into the *top event* if not mitigated. Further discussion of the threats is found in section 2 on page 9.

1.2.4. Consequences

The consequence of the *top event* depends on the efficiency of the mitigation barriers and external parameters. In fire safety engineering, mitigation strategies are generally categorized into passive and active fire protection measures [16]. Compliance with European standards, such as EN 13501-5, *Fire classification of construction products and building elements – Part 5: Classification using data from external fire exposure to roofs tests* [17], is achieved through standardized testing protocols. These protocols are designed to reduce the probability that a defined *top event* will escalate into severe consequences.

As such, the outcome of the *top event* can range from localized damage, as illustrated in Figure 2, to flame spread along the roof or into the building. For fires related to BAPV systems, the cavity between the roof surface and the PV modules introduces additional consequences compared to roof constructions without BAPV systems. This aspect is discussed further in section 3.

Due to the limited availability of data describing PV-related fire risks, the definition of a PV-related fire remains ambiguous. This issue is highlighted by Mohd Nizam Ong et al., who estimated an annual frequency of 29 PV-related fires per gigawatt (GW) installed capacity. However, the consequences of these fires are largely unknown, aa global media coverage tends to focus only on the most severe incidents.

Figure 2 – Charred area on the roof surface caused by direct current arcing related to a faulty component of a BAPV system. The component was not located in the cavity between the roof surface and the BAPV module. Shared with permission from the property owner (confidential).

1.2.5. Major Accident Events

PV-related fires reported in the media tend to represent the most severe incidents, often involving higher economic costs and broader impacts on the environment, society, and public risk perception of PV systems. Recent large-scale PV-related fires include an IKEA distribution center in Illinois, US (2025) [18]. the Don Bosco School in Belgium (2025) [19], two incidents in Northern Germany (2025) [20], the Miramar Shopping Mall in Spain (2025) [21], Lidl's storage facility in Peterborough, UK (2024) [22], an industrial building in Switzerland (2023) [23], a poultry farm in Italy (2023) [24], and the British museum "We the curious" in 2022 [25].

A common feature of these incidents was fire propagation along the building envelope, with several cases involving secondary spread from the roof into the subjacent fire compartment. Intuitively, flame spread into the building is considered more severe than spread along the roof, as the transition from a roof fire to a structural fire represents an escalation in consequences. Although internal flame spread depends on the prior development of the external fire, fire propagation at the roof level alone can still lead to considerable economic losses due to water or smoke damage affecting the underlying compartment, which may independently cause business disruption. For this reason, both outcomes are regarded as significant and undesirable, and are therefore defined as the major accident events (MAEs) in the Bow Tie model.

MAE 1: *Flame spread along the roof.*
MAE 2: *Flame spread into subjacent fire compartment.*

Consequently, the aim of this report is to identify and analyse factors and parameters that can serve as reduction and mitigation barriers, as discussed in sections 2 and 3. Subsequently, section 4 examines the current development of test methods assessing the effectiveness of these barriers. Finally, section 5 presents a discussion of the findings, wherein the author proposes an outline for a test method based on relevant input parameters and quantifiable metrics.

2. CAUSE OF FIRES ASSOCIATED WITH PV SYSTEMS

Given that direct current (DC) is intrinsic to photovoltaic (PV) systems, converting solar radiation into electricity, the PV system itself represents a possible ignition source. Unlike systems based on alternating current (AC), an electric failure in a DC system permits the establishment of self-sustained electric arcing which can reach extremely high temperatures up to 6500 K [26, Ch. 11], [27]. Research by Hastings et al. indicates that DC arcs with power levels of 200 W, 400 W, and 800 W can ignite plastics within approximately 4 s, 2 s, and 0.3 s, respectively [27].

Based on over 600 inspections of PV systems worldwide, Clean Energy Associates (CEA) reported that 97% of all audited systems had major safety concerns [28]. Similarly, HelioVolta's 2023 *SolarGrade PV Health Report*, which analyzed more than 60,000 data points from hundreds of inspections, found that 62% of inspections identified safety issues requiring urgent correction [29]. HelioVolta also reported that 91% of those issues were on the DC side of the installation, and that 59% of all issues were related to field-made connectors and wire management [29]. In their 2024 *SolarGrade PV Health Report*, HelioVolta concluded that critical issues take time to develop, which is why most were found during inspections of operating PV systems rather than newly installed ones [30]. The inspections and data presented in the reports from CEA and HelioVolta do not solely focus on fire-related risks associated with building-applied PV systems. Instead, they provide a broader assessment of risks related to system performance, on-site personnel safety, and fire hazards.

For that reason, the following section is mainly based on an analysis conducted by Mohd Nizam Ong et al. in 2021, which estimated that only 67% of PV-related fires originate from six specific PV system components, with the remainder attributed to external or unknown ignition sources, as shown in

Figure 3. As stated in the peer-reviewed paper, the analysis was based on all public available at the time of the analysis. However, the quality and quantity of the available data was limited.

No matter the limitations ascribed to the analysed data quality and quantity, the study by Mohd Nizam Ong et al. does highlight relevant failure modes and thus threats which can lead to the *top event* of the Bow Tie analysis, if not eliminated or mitigated by implementation of adequate reduction barriers.

In general, two categories of threats have the possibility of representing paths that leads to the *top event* – the formation of competent ignition source: i) Ignition caused by the PV system, and ii) ignition caused by an external source of ignition.

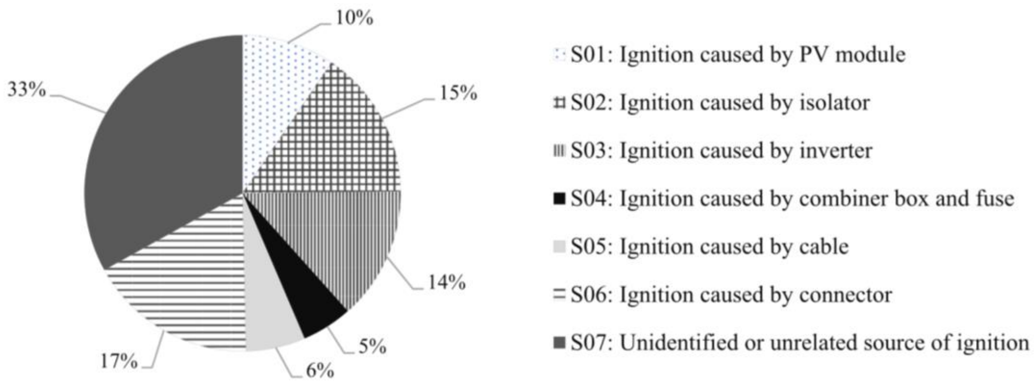

Figure 3 - Cause of PV-related fires. From: Mohd Nizam Ong et al. [8]

2.1. Ignition sources related to the PV system

Forensic and historical investigations conducted by the British Research Establishment (BRE) identified six PV system components capable of causing ignition [31]. Analysing data from Australia, Germany, and the UK, Mohd Nizam Ong et al. determined that components susceptible to human errors and design failures, such as connectors (17%), isolators (15%), inverters (14%), and combiner boxes (5%), accounted for a significantly higher proportion of PV-related fires compared to pre-assembled components like PV modules (10%) and cables (6%) [8]. It is important to note that these frequencies are derived from non-homogeneous and limited datasets, and the analysis did not distinguish between BIPV and BAPV systems. However, the influence of installation methods is examined below alongside relevant component-specific factors that may affect failure likelihood and ignition risk. Lastly, the observed correlation between failure rates and susceptibility to human error does not inherently imply that these components are unsafe; rather, it highlights the impact of insufficiently trained personnel.

2.1.1. Connectors

No connector standard exists within the PV industry, but to some extend the connector MultiContact 4 (MC4) manufactured by Stäubli have become a de facto standard, which is emphasised by the term "MC4-compatible". More than 200 similar, but not identical, connectors are produced by other manufacturers [32] and connector-mismatch across different brands might lead to build-up of oxides on the electric contacts, increased electrical resistance, temperature rise, and finally DC arcing. Sepanski et al. highlighted a study by Lukas Von Ballmoos, who examined resistance increase for several connections and connector-mismatch of "MC4-compatible" connectors before and after artificial ageing [33], [34]. After the artificial aging, the resistance increased around 20 % for the original connectors, whereas cross-mating of connectors from various manufactures resulted in a resistance increase of up to 180% and measured temperatures of 200 °C. A comprehensive overview of failure types related to the connectors are described in the report "Quantification of Technical Risks in PV Power Systems" published by the International Energy Agency Photovoltaic Power Systems Programme (IEA-PVPS) where connector-mismatch, defect connectors, and incorrect crimping are all defined as failures that can directly cause a fire [35].

Most connectors can be pre-installed on the PV modules from the factory and thus reduce probability of failure. Yet, extension cables are requisite for parts of the remaining PV system infrastructure if the system design prompts the need for longer cables and thus manually installed connectors, which introduce failures caused by human errors. Finally, Connection-mismatch can occur between pre-installed connectors on different components of the PV system such as the end of a PV panel string, the inverter and an extension cable between PV string and inverter.

2.1.2. Isolators

Isolators, also referred to as switches, are classified as either DC or AC switches depending on their placement relative to the inverter. DC switches disconnect power from part or all the PV system to the inverter, whereas AC switches isolate the AC current between the inverter and the property's distribution board. In 2012, Australia mandated the use of DC switches; however, inspection data from 2021 identified them as the leading cause of system failures in conventional PV systems, prompting the mandate's repeal [36]. Nonetheless, the Danish Institute for Fire and Security (DBI) has mandated the integration of DC switches in its 2024 guidelines, where the presence of DC current within the fire compartment cannot be eliminated through alternative design measures [37]. This requirement is intended to safeguard the fire and rescue service during compartment fires that are unrelated to the PV installation. The guideline further stipulates that the entire PV system, including the DC switch, must undergo annual inspection to ensure continued operational safety [37].

2.1.3. Inverters

Inverters are generally classified into three categories i) micro-, ii) string-, and iii) central inverters, and all inverter types convert the direct current (DC) generated by the PV modules into alternating current (AC) which can be utilised directly or fed into the grid. The three types of inverters differentiate by location and the maximum current and amperage they transform.

As the name implies, microinverters are installed at module- or bi-module-level and thus, the input current and amperage are low. For string inverters, PV modules are series-connected to a maximum current of 1000 V_{dc} or 1500 V_{dc} depending on the inverter, cable and module specifications. Several strings can be connected to a string inverter and the effect of a single inverter varies between a few kW to hundreds of kW. Some string inverters are central inverters, but not all central inverters are string inverters as some central inverters can accept both high amperage voltage inputs.

According to Coonick's BRE report, inverters, unlike switches, connectors, and cables, are intelligent components capable of handling certain failure types autonomously, mitigating the risk of severe consequences in the event of electrical malfunctions [31].

2.1.4. Combiner Boxes

Combiner boxes are used to combine several strings of series-connected PV modules into parallel whereupon multiple combiner boxes are connected to a central inverter. The use of combiner boxes introduces additional components to the PV system, and the combination of series- and parallel connected PV modules cause a combination of high current and high voltage. Additional components increase the likelihood of failure within the system and the combination of high current and high voltage increase the effect of a DC arc being the worst-case consequence of an electric failure within the system. Like the competent ignition sources ascribed to connectors, poor connections within the combiner boxes can lead to increased resistance, which can ultimately facilitate the formation of DC-arcing and thus the formation of a competent ignition source [8].

2.1.5. Cables

Poor design or installation practices can lead to the use of undersized cables or mechanical damage to the insulation caused by sharp edges, as well as animal bites and degradation of the cable insulation, which are all failures types that can directly cause ignition [28], [33], [35], [38].

2.1.6. PV modules

Despite the standardized product tests of PV modules outlined in EN IEC 61730-2 [39], PV modules have been identified as potential sources of ignition. Studies by Mohd Nizam Ong et al. and Herz et al. have quantified technical risks associated with PV module failures [8], [35]. Common failure modes include PV cell cracks, caused during manufacturing, transport, or installation, which can increase fire risk. Additional failure types, such as front, cell, and backsheet delamination, encapsulant discoloration, and backsheet cracking, may also lead to the *top event* of the Bow Tie model in section 1.2.

2.2. Ignition sources not related to the PV system

The term *"PV-related fire"* is consistently used throughout the document to acknowledge that not all such incidents originate from faults within the PV system itself. This terminology aligns with the principles of the Bow Tie risk model, which systematically distinguishes between threats and consequences. Accordingly, some PV-related fires may be initiated by external ignition sources rather than by defective PV components, as highlighted by Mohd Nizam Ong et al. [8]. Similar findings have been reported in the Netherlands, where 70 out of 152 PV-related fires were examined and, in approximately half of the cases, the cause of ignition was either unknown or unrelated to the PV system[40].

However, available data on the root causes of PV-related fires remains limited. One of the most well-known examples of a significant PV-related fire not caused by the PV system itself is the ASKO fire in Norway [41], while the incident at Gedved Skole in Denmark may serve as another illustrative case [42].

In the Norwegian example, the fire originated from a forklift located inside the storage facility. In the case of Gedved Skole, the ignition source could not be identified. Nevertheless, in both instances, the presence of BAPV modules on the roof significantly exacerbated the consequences which will be discussed in section 3.

These cases underscore that the high proportion of unidentified or non-PV-related ignition sources associated with PV-related fires suggests that the mere presence of a BAPV system increases the overall number of threats. Conventional ignition sources, such as fireworks, airborne burning brands, or flame spread to the building envelope from a compartment fire, continue to represent credible threats that may lead to the *top event* described in the Bow Tie model presented in section 1.2.

3. FACTORS AFFECTING CONSEQUENCES

In case the *top event*, a competent ignition source, is triggered, the outcome of the fire depends on the status of the active and/or passive migration barriers present to prevent the consequences defined as the *major accident event*s, MAE I and MAE II. On a conventional flat roof construction, without a BAPV system, the consequences are mitigated through local, regional or national building regulations or codes. Often, the regulations define the requirements to a building's roof construction, in the form of a fire classification, depending on its location, usage, and dimensions. In Europe classification of roof surfaces are a non-harmonised standard with four classification systems [17], where the fire classification depends on the test outcome of four different test methods defined in CEN/TS 1187 [43]. No matter the test method, the aim of the tests are to quantify the roof constructions reaction to fire, based on flame spread along and into the examined test samples [17]. Hence, for roof constructions without a BAPV system, compliance with regulatory classification requirements serves as a mitigation barrier, preventing a direct path from the *top event* to one of the two *major accident event*s defined in section 1.2.5.

Large-scale experiments [44], [45], [46], [47], [48], as well as PV-related fires in countries using each of the four classification systems defined in EN 13501-5 [17], illustrate that introduction of a BAPV system can render the regulatory classification requirements inadequate. This occurs because the mitigation barrier was bypassed, allowing a direct path from the *top event* to the MAEs, resulting in flame spread along and into the building. Research have been conducted to examine the parameters that independently, or combined, have the potential to bypass the mitigation barrier based on fundamental fire safety science and engineering principles.

In general, the parameters can be divided into two categories, design parameters and parameters associated with the ambient conditions. Here, design parameters are defined as parameters that can be altered through conscious choices or engineering, whereas parameters which cannot be defined as a design parameter are considered ambient parameters. Based on a systematic evaluation of both design parameters and ambient parameters in the following subsections, the significance of the most relevant parameters is evaluated in the end of the section.

3.1. Design parameters

Large- and medium-scale experiments, along with PV-related fire incidents, demonstrate that flame spread can occur in the cavity between the roof surface and the backside of the PV module, despite the roof construction's fire classification when tested without PV modules. The following subsections discuss parameters that have the potential to affect the consequences of a PV-related fire.

3.1.1. Mounting system – cavity geometry

BAPV modules are installed on roofs using mounting systems which are either ballasted, glued, or mechanically fixed to the roof constructions. In addition to securing the PV modules, the location and geometry of the mounting system ensure optimised orientation and inclination of the PV modules with the aim of high system efficiency and thus return of investment. Inclined PV modules are almost always rotated around their longest side if installed on flat roof constructions. Based on the existing research, the mounting system can affect the outcome of a fire as it can i) represent an additional fuel load on the roof construction and ii) alter the fire dynamic system in the cavity between the roof construction and PV module.

The former was illustrated in large-scale experiments conducted by Kristensen & Jomaas, where six PV modules installed on an East/West-orientated mounting system made of aluminium sections and connected by plastic feet, was tested on four roof mock-ups [44], [49]. In all four tests, the fire propagated along the compliant roof (B_{ROOF}(t2)), below all six modules. In addition, the plastic components of the mounting system continued burning for a longer duration than the fire below the PV modules, increasing the heat transfer to the subjacent insulation. Thus, the experiments illustrated that the increased fuel load associated with the specific mounting system had the potential to increase the consequences of the *top event*.

Increased re-radiation towards a flat roof construction based on the gap height and inclination, was identified in three independent series of steady-state experiments [50], [51] based on the set-up defined in [52]. All three experiments were conducted with a gas burner and the increased radiation to the subjacent surface was caused by deflection of the flame from the gas burner and thus and increased view factor[1] between the flame and roof [54]. Ju et al. correlated the experiments with flow calculations, illustrating higher flow of combustible gases, thus longer flame extension, below the most elevated section of an inclined barrier [51]. Tang et al. found that higher radiative heat transfer from the extended flames did increase the heat fluxes towards the subjacent roof near the gas burner [50], despite a reduced the view factor between deflected flame and subjacent roof [54]. However, an inclination around 15° yielded the highest radiative heat flux distribution below the most elevated section of the barrier, since increased distance from the gas burner caused a lower reduction of re-radiation, when compared to tests with higher inclinations [54]. Finally, the work by Ju et al. and Tang et al. illustrated that reduction of gap height increased re-radiation. Based on the UL 790 test method, Backstrom and Tabaddor examined how the installation an inert surface affected the heat flux towards the inclined subjacent test board. They found that a gap height of 5 inches (12.7 cm) caused a significantly higher heat flux that the heat flux measured in the base line tests without the PV module substitute and in the tests with a gap height of 10 inches [55].

The influence of the gap height in horizontal cavities was further examined in two series of transient flame spread studies [56] [57]. In fundamental flame spread studies on the reference material polymethyl methacrylate (PMMA), it was identified that a critical gap height existed for cavities between a horizontal fuel surface and an inert parallel barrier. A slow and steady flame spread rate was observed for gap heights exceeding the critical gap distance. In contrast, when the gap height was below the critical gap height, a positive heat feedback loop promoted a transition from slow to rapidly accelerating flame spread [56].

The existence of the critical gap height was also observed when the PMMA was replaced by a roof construction mock-ups [57]. However, a binary flame spread scenario was observed along the compliant PVC-based roofing membrane (B_{ROOF}(t4) since gap heights above the critical gap height caused no flame spread outside the domain of the ignition source, whereas gap height below the critical gap height resulted in flame spread along the full test set-up [57]. Inclination of the PV modules from horizontal increased the critical gap height and

[1] View factor is *the fraction of the radiation leaving one surface that is intercepted by another surface* [53, p. 828].

caused faster flame spread rates, but no significant difference was observed between tests conducted wit 10°, 13° and 15° [57].

Stølen, Fjærestad, and Mikaelsen conducted a series of experiments demonstrating that the critical gap height is dependent on the heat release rate (HRR) of the ignition source [58]. Thus, the competent ignition source, defined as the *top event* in the Bow Tie model, is not a fixed parameter, but a parameter that depends on the fire dynamic system. The relation between critical gap height and HRR was also indirectly observed in the work by Kristensen, Jacobs and Jomaas as the limited width of their roof mock-ups only allowed flame spread in one direction. As such the width of the set-up restricted the HRR from roofing membrane, which prevented selfsustained flame spread as the flame front reached a specific local gap height, no matter the initial gap height at the location of the ignition source [57].

The importance of re-radiation as decisive factor has furthermore been illustrated in large-scale tests, where self-sustained flame spread occurred below arrays with four or six PV modules installed in an east/west-orientated mounting system on either B_{ROOF}(t1)- or B_{ROOF}(t2)-classified single ply PVC-based roofing membranes. In all tests [44], [45], [49] [46], [47], besides one [48], self-sustained flame spread within the cavity between the PV array and roof surface occurred, whereas no significant self-sustained flame spread occurred outside the arrays. In the single outlier [48], a 12 mm thick cement fiber boards was tested as mitigation layer between a PVC-based roofing membrane and an EPS insulated roof built-up.

As such, the mounting system serves as both a potential fuel load and critical component of the BAPV system which determine the geometry of the cavity between the roof surface and backside of the PV modules. A critical gap height between the roof surface and lowest section of the PV module can be determined for a specific ignition source. Thus, it should also be possible to determine a critical ignition source for a given gap height, where an ignition source with a HRR below the critical HRR cause no self-sustained flame spread, and vice versa. Despite the identification of the critical gap height and critical ignition source, other parameters not related to the fire-related risk, such as aesthetics, wind load and system efficiency might have a larger influence on the gap height between the PV module and roof construction.

Consequently, gap height is not necessarily a design parameter that can be adjusted for BAPV systems to improve fire safety, but it is an essential design parameter to understand the influence of. The reason for that is, that the gap height and inclination affect the fire dynamics and with that, the consequences of the *top event* in the form of flame spread along the roof and heat transfer into the building.

3.1.2. Roof construction

Severity of the consequence associated with flame spread in the cavity between the roof surface and a BAPV module, discussed in 3.1.1, can depend on the roof construction built-up hosting the BAPV system.

Essentially, the roof built-up can be separated in up to three main components, the roof surface, insulation and loadbearing components. It is acknowledged that other components, such as fasteners or a moisture/vapour barrier, are present in most roof construction but no known research have studied the influence of these.

Backstrom and Tabaddor did examine flame spread below PV modules for various roof surfaces, including wooden shakes (class C), architectural shingles (class A), a Class A single-ply membrane, and hot mopped asphalt (class A). However, they adjusted multiple variables simultaneously and as such, the effect of the roof surface itself could not be quantified [55].

No other known work has systematically examined the influence of the roof surface below PV modules. However, experience from conducting the experiments of flame spread along roof mock-ups [57], illustrated the sensitivity of parameters affecting the fire dynamics in the cavity. The finding was not mentioned in the peer-reviewed journal paper or doctoral dissertation [54], since it resulted from a simple human error and the specific tests are not part of the published work. During the experimental campaign, the thickness of the compliant PVC-based roofing membrane ($B_{ROOF}(t4)$) was unintentionally reduced with 20%, from 1.5 mm to 1.2 mm, when one roll of membrane replaced another without it being noticed. The reduction of membrane thickness was efficiently a reduction of fuel load on the roof mock-up and consequently, the thinner roofing membrane reduced the cumulative radiative heat transfer towards the pre-heating zone. As a result, no selfsustained flame spread occurred for the thinner membrane, whereas it did for the thicker membrane.

Based on this, fundamental flame spread theory [59] indicates that a thickness increase of a homogeneous, combustible roofing membrane does increase the fuel load on the roof, which will result in enhanced pre-heating ahead of the flame front and thus faster flame spread if other parameters remain constant. However, an increased fuel thickness should also cause a slower moving pyrolysis zone, hence increased radiative heat transfer towards the subjacent insulation, as the pyrolysis zone are assumed to behave as a pool fire with a constant surface temperature and as such, constant mass loss and heat release rates.

The relationship between heat transfer towards the insulation material below the roofing membrane and the speed of the pyrolysis zone, was illustrated in the medium-scale tests by Kristensen, Jacobs and Jomaas. In the tests with horizontal PV modules, higher temperatures were measured in the test with the slowest flame spread rate and thus, speed of the pyrolysis zone.

Although flame spread along the roof is considered a *major accident event* by itself (MAE 1), the consequences of flame spread into the building is considered a more severe outcome of a PV-related fire. Thus, the subjacent roof constructions response to the heat transfer have been quantified in both medium-scale and large-scale tests.

Backstrom et al. [55] and Stølen et al. [58] conducted their flame spread tests on an underlay of plywood with the purpose of identifying burn through. PU Europe, Kingspan and the European Manufactures of Expanded Polystyre (EUMEPS) all published large-scale tests, with the purpose of either validation of their products [38], comparison with a competing product category [45], [46] or test of mitigation layers [48].

Kristensen and Jomaas also conducted a series of large-scale tests with the purpose of testing various mitigation layers installed on top of an EPS (non FR) insulated roof construction [44]. All test campaigns were conducted with a compliant PVC-based single ply membrane ($B_{ROOF}(t1)$), besides Kristensen and Jomaas who tested with a compliant PVC-based single ply membrane ($B_{ROOF}(t2)$). Temperature development was quantified through measurements taken below the roofing membrane, within the insulation layers, and on the underlying steel deck. In cases where the mitigation layer above an EPS-insulated roof failed mechanically, two distinct outcomes were observed. The EPS either ignited and supported self-sustained flame spread [44], or it ignited, melted, and subsequently self-extinguished [47]. In tests where the mitigation layer above the EPS-insulation did not fail mechanically, the subjacent layer of EPS melted at the location of the ignition source [48] or below the area with flame spread [44] depending on the thermal characteristics of the mitigation layer.

Comparison tests between PIR insulation and mineral wool all focused on temperature development within the insulation materials after the fire self-extinguished [45], [46], as none of the products contributed to the fire. None of the tests assess the safety level of the roof build-ups, since acceptance criteria is considered a regulatory definition depending on the acceptable level of risk, where the requirements are defined by authorities or insurance companies - as de facto-regulators, in absence of local, regional or national regulations.

3.1.3. PV module

Photovoltaic modules for BAPV applications are all constructed with front sheet of glass, a combustible encapsulant (EVA or PET), and a backside of either another glass layer or a plastic foil. Glass/foil-modules are slightly cheaper that glass/glass modules and thus compose the majority of the marked. The foil on most glass/foil module are a polyvinyl fluoride such as the products Tedlar or Kynar [54], as the modules are exposed to extreme thermal stresses during their lifespan, which can lead to damaged foil backsheets that reduce system efficiency or increase the risk of electrocution [35].

No published research has verified that flame spread in the cavity below glass/foil-modules can be prevented, if the modules are replaced by glass/glass-modules when tested as a building applied system on flat roofs. However, bench-scale tests by Fjærestad et al. have identified a significant difference when PV modules are tested vertically as a building integrated PV module [60].

No significant difference were observed in the flame spread tests along PMMA when tests were conducted with respectively glass/foil modules and an inert stainless steel board [56], whereas a small difference in flame spread length were observed when stainless steel board and PV modules was used above the compliant PVC-based single ply membrane (B_{ROOF}(t2)) on the roof mock-ups [57]. However, no self-sustained flame spread had occurred along any of the PV modules used for the test, which indicates that the modules should be considered a limited fuel load.

Based on current research, it is assumed that the fuel load of the PV modules and their radiative heat transfer to the subjacent roof construction are less significant than the contribution from a combustible roofing membrane and the effects of re-radiation within the cavity beneath a BAPV array.

3.2. Ambient parameters

Two ambient parameters are considered within the report, wind load and ambient temperature as they are both parameters that fluctuates and depend on the location of the building with a BAPV system.

3.2.1. Wind load

Fundamentally, a wind load along a horizontal roof construction facilitates either concurrent or opposed flame spread depending on whether the wind blows in the direction of, or against, the flame spread direction [59]. Faster wind loads can accelerate flame spread, but too fast wind loads during the development of a competent ignition source can dilute the concentration of combustible pyrolysis gases to a level below the materials lower flammability limit (LFL [61]), and thus prevent flame spread outside the domain of the ignition source [54]. The consequences of too high wind loads were described in a series of initial test conducted as part of Kristensen's work [54, Sec. 4.5], which have not been published in any peer reviewed journal since the experiments contained too many variables, including inconsistent variation of the extraction flow, thus local wind load.

No matter the wind load, the deflection of the flames in the cavity below a PV array essentially alter the flame shape towards a concurrent flame spread scenario, as the deflected flame increase the view factor between the flame and subjacent roof surface, thus heat flux towards the pre-heating zone.

Finally, wind load is a stochastic variable, and a critical wind condition for one fire dynamics scenario may not be critical for another.

3.2.2. Ambient temperature

Higher ambient temperature leads to a reduced preheating phase before ignition, thus faster flame spread [59]. The reason for that is, that less energy is required to elevate the temperature of a material from a high ambient temperature to its ignition temperature.

For materials with high ignition temperatures, the difference in fire behavior between tests conducted at initial ambient temperatures of 10 °C and 35 °C may be limited. However, when comparing different products, the ambient temperature should be kept as consistent as possible across tests, as the fire dynamics system is sensitive to minor variations, - highlighted by the identification of critical parameters such as gap height and ignition source strength.

3.3. Relevant input parameters and consequences

Based on the parameters discussed in sections 3.1 and 3.2, the following two subsections are used to evaluate what affects the outcome of a *top event*, in the form of a *competent ignition source*, with the aim of preventing the two major accident events MAE 1, *Flame spread along the roof*, and MAE 2, *Flame spread into subjacent fire compartment*.

With MAE 1 being prerequisite of MAE 2, section 3.3.1 pivots around parameters affecting flame spread whereas section 3.3.2 focuses on flame spread into the building. The underlying basis of both sections is BAPV systems on flat roof constructions as seen on commercial and Industrial (C&I) buildings. Only flame spread along the roof, and from the roof into the subjacent fire compartment through the roof construction is considered. Thus, the following sections do not consider flame spread into the building through roof penetrations, such as skylights or ventilations systems.

3.3.1. MAE 1 Flame spread along the roof

Two factors determine the severity of *top event*: i) the upper surface of the roof and ii) the cavity between the BAPV module and the roof surface. Finally, it is acknowledged that the wind load can affect the fire-related risk but should not necessarily be considered a parameter that affects the consequences of the top event.

Essentially, flame spread does not occur along non-combustible roof surfaces, but the cavity between the roof and PV module can facilitate flame spread along all combustible roofing materials, despite compliance with the existing classification system for roof constructions in Europe, EN 13501-5. As such, even roofing membrane classified B_{ROOF}(t1, t2, t3 or t4) should be considered a fuel load, where the flame spread rate depends on material properties and mass of the membrane. Thinner membranes might be less prone facilitate flame spread, as a reduced thickness essentially is a fuel reduction and thus, a limitation of the preheating time ahead of the flame front.

Modified fire dynamics of the roof, driven by the introduction of the cavity between the BAPV module and roof, is the primary factor influencing the flame spread as described in section 3.1.1. The section also defined that the consequences of the *top event* can be mitigated significantly if the gap distance between the BAPV modules and subjacent roof exceeds the critical gap height. However, the critical gap heights rely on the magnitude of the ignition sources and for gap heights below the critical gap height, the geometry acts as a catalyst rather than a barrier or mitigating factor. Understanding that some geometries serve as better catalysts than others enable the identification of configurations with the least severe consequences, allowing them to be considered as potential mitigation barriers.

It is acknowledged that the wind load can be considered a critical parameter during the phase where an initial fire transitions into a competent ignition source, which can propagate in the cavity between the roof construction and a BAPV array. However, the influence of the wind load is considered limited during flame spread in the cavity, as the deflection of the flame below the BAPV module essentially renders all flame spread, concurrent.

3.3.2. MAE 2 Flame spread into subjacent fire compartment

In most building regulations, the building envelope, comprising the roof and façades, defines the perimeter of a construction with one or more fire compartments. In case a fire develops within a fire compartment, compliance with the building regulations should prevent flame spread to other fire compartment within a given time span.

For this reason, flame spread along the building envelope is generally not tolerated, as it can bypass the intended fire strategy. This risk was evident in the façade fires in London [62] and Valencia [63], where fire spread from one compartment to another via the building envelope. Similarly, the ASKO fire in Norway demonstrated that roof constructions with BAPV modules have the potential to compromise traditional fire compartmentation [41]. In this case, a compartment fire breached the roof, spread along the roof construction with BAPV modules, and entered the neighbouring fire compartment.

Since the introduction of BAPV modules enable flame spread along parts of the building envelope, the fire safety strategy of a building with BAPV modules should consider and mitigate the consequences, so that MAE 1 cannot develop into MAE 2.

With MAE 1 being prerequisite for MAE 2, factors affecting one *major accident event* also affects the other. However, the roof construction built-up serves as a decisive factor which set apart MAE 1 from MAE 2, thus severe consequences from critical consequences. From the large and medium-scale experiments described in section 3.1.2, several failure modes were identified as both significant temperature increase, ignition and deformation of the subjacent insulation material should be considered when evaluating the potential outcome of a BAPV-related fire.

3.3.3. Prioritisation of input parameters

Based on the preceding discussion of relevant research, two input parameters are found essential for assessing the potential consequences of the *top event*, a competent ignition source. In addition, two additional parameters are found to be relevant, but non-essential.

The roof construction build-up, including the roof surface and underlying construction materials, is identified as the single most critical input parameter. This is primarily due to the fact that roofs compliant with the current European classification standard, EN 13501-5 [17], may perform inadequately when a BAPV system is introduced, as such systems can facilitate self-sustained flame spread. Consequently, the roof surface constitutes a fuel load, and the overall roof build-up, including mitigation layers, can be the decisive factor in determining whether fire propagation remains confined to the roof surface (MAE 1) or breaches into the subjacent compartment (MAE 2).

The geometry of the cavity formed between the roof surface and the underside of the PV modules is identified as the second most critical parameter influencing fire dynamics. Specifically, the gap height between the roof surface and the lowest part of the PV modules can be a decisive factor in preventing self-sustained flame spread, provided it exceeds the critical gap height for the given fire dynamic system. However, the critical gap height is not an independent parameter; it depends on other factors within the fire dynamic system, such as the heat release rate (HRR) from the ignition source during the initial phase of a fire. Nonetheless, lower gap heights increase the likelihood of self-sustained flame spread and enhance heat transfer to the underlying roof construction. Therefore, the cavity geometry can contribute to both *major accident event*s: flame spread along the roof (MAE 1) and flame spread into the building (MAE 2).

Finally, it is acknowledged that both wind load and the type of PV module can significantly influence the dynamics of a PV-related fire, which justifies their inclusion as input parameters in a test method. Wind load, as a stochastic variable, can in open roof constructions without a BAPV system induce either concurrent or opposed flame spread. As a result, it may influence the fire behaviour even when semi concurrent flame propagation is facilitated by the presence of a cavity. The influence of PV module type remains a subject of ongoing research. While PV modules with plastic backsheets possess a slightly higher fuel load compared to those with glass backsheets, the additional fuel load might be insignificant relative to the fuel load of the roof surface. Currently, there is no publicly available research identifying PV module type as a critical parameter. Consequently, it is recommended to further examine the effect of the PV module type before mandating tests for each combination of roof construction build-up and individual PV modules.

4. DEVELOPMENT OF TEST METHODS

Several test methods have been developed in addition to the large-scale tests mentioned in Section 3. Unlike the more research-focused work primarily discussed in Section 3, these test methods aim to compare test samples and identify roof built-ups with the lowest potential consequences.

Overall, the tests methods can be divided to three subcategories. Large-scale tests, test methods based on CEN/TS 1187:2012, and test methods based on other test methods.

4.1. Large-scale and reduced large-scale tests

Large-scale tests with a flat roof construction mock-up and four PV modules installed on mounting system for east/west-orientated PV modules have developed into a de-facto test method for manufactures of, mainly, insulation products. The test method mainly draws inspiration from the large-scale tests conducted by Kristensen and Jomaas in 2016 [49], [44], with two main deviations: a) the number of modules are reduced from six to four, and ii) a gas burner is used for ignition rather than a wood crib.

Tests published by PU Europe [45], EUMEPS [47], [48], and Kingspan [46] were all conducted on square roof surfaces with side lengths ranging from 6 m to 7 m. In all tests, ignition was performed using a gas burner defined in CENELEC CLC/TR 50670:2016 [64] with an output of 15 kW (see section 0). However, there is no consensus on the ignition duration, which varies across the four documents: 15 minutes, 10 minutes, 10 minutes, and 3 minutes, respectively. The vast majority of the large-scale tests are conducted outdoor, with parts of Kingspan's test series being the sole exception [46].

In 2025, the Slovenian National Building and Civil Engineering Institute (ZAG), published the description of a reduced test method for indoor examination of roof construction with respectively one or four PV modules on roof mock-ups with side lengths of respectively 200 cm times 200cm, or 400 cm times 350 cm [65]. Similar to the other large-scale tests, the test method draws inspiration from the tests by Kristensen and Jomaas [49], [44] and use wood crib with an theoretical peak heat release rate of 16.6 kW [65]. Parts of the test methods is well defined whereas other sections allow interpretation. Common for all large-scale test methods are, that the ignition source is placed below lowest part of the inclined PV module with around 10 cm between the edge of the ignition source and PV module.

In general, the large-scale tests are considered as an adequate method to determine the consequences of BAPV-rated fires as it represents a system test, which consider the type of roofing membrane, the geometry between the roof surface and PV module, and the roof construction built up. However, none of the test methods suggest quantifiable parameters, nor pass/fail criteria, that can be used for classification of the combined roof build-up, mounting system and PV module. In addition, none of the published test have been repeated, nor reproduced, so the influence of the ambient conditions, test site and test personnel are unknown, although it is expected that large-scale testing entails a lower degree of repeatability than smaller scale tests [66].

4.2. Tests based on CEN/TS 1187:2012

Various stakeholders have modified three of the four European test methods which are used for classification based on external fire exposure to roofs, as defined in EN 13501-5 [17] and CEN/TS 1187 [43]. The three test methods are based on test methods 1-3 in CEN/TS 1187, whereas no known work have attempted to modify test method 4.

4.2.1. Test method 1

In 2014, a German collaboration between TüV Reinland, Currenta gmbH and Bergische Universität Wuppertal published the outcome of a comparative study [67]. Whereas the main objective of the work might have been the design of a test method for roof constructions in combination with BAPV modules, the focus was on the development of a gas burner to replace the wood wool basket, which is the ignition source used in CEN/TS 1187 test method 1 [43]. Thus, the work presented in the report serves as the origin for the gas burner used in CENELEC CLC/TR 50670:2016 [64] and the majority of large-scale experiments discussed in section 4.1.

In the report, repeated tests are conducted with both the wood wool basket and gas burner on respectively inert surfaces, as well as roof constructions with and without PV module substitutes. Tests conducted on an inert surface were used to fine-tune the gas burner's heat release rate (HRR) and burning time to match the temperatures measured near the ignition source in tests using the wood wool basket. The calibration of gas burner was conducted with and without an inert PV module substitute which was elevated slightly more than the 20 cm high wood wool basket. The calibration resulted in an HRR of 15 kW and a burning time of 10 minutes.

The subsequent validation test was performed on roof construction mock-ups without PV modules, nor PV module substitutes. The report concludes that the developed gas burner is a suitable substitute for the wood wool basket in testing roof constructions with PV modules, primarily due to its lower profile compared to the original ignition source [67].

The report's test matrix includes roof constructions combined with different PV modules. However, the test results are not presented. While the report emphasizes the need to test roof constructions with PV modules, it fails to address the influence of the cavity geometry between the roof surface and the backside of the PV module.

4.2.2. Test method 2

Stølen et al. conducted a series of tests based on a modified version of CEN/TS 1187 test method 2 [23], where an inert surface was installed above the test deck at gap heights of respectively 6 cm, 9 cm, 12 cm and baseline tests without a panel [29]. In all tests, the test specimen was a bitumen membrane tested on a 22 mm chipboard. The flame spread length only differentiated significantly from the baseline tests, in the tests conducted with a gap height of 6 cm.

Although no significant flame spread length increase was observed for the gap height of 12 cm, the report does include medium-scale tests with a gap height of 12 cm. Based on those tests, the outcome of the modified CEN/TS 1187 test method 2 is validated as is no significant difference between the flame spread length achieved with and without the PV module substitute in the medium-scale tests.

The modified version of CEN/TS 1187 test method 2 are the only tests repeated within the report and thus, the report should be considered a preliminary study, rather than a dedicated development of a test method. The tests do take re-radiation into account, but the influence of geometric parameters, such as PV or roof inclination, might be hard to examine due to the limited dimensions of the test set-up. In the specific test series by Stølen et al., only the gap height is varied whereas the influence of other parameters is not examined.

4.2.3. Test method 3

The description of a test method based on CEN/TS 1187 test method 3 was published by Centre Scientifique et Techique du Batiment (CSTB) in 2012 [68]. The document does not include any validation of the test method. When comparing the illustrations in Figure 4 with the description of test method 3 in CEN/TS 1187 [23], an increased distance between the radiant panel and the roof surface is seen in the modified test method. In addition, the PV module, partly, shields radiation towards the roof surface. The test method was described in presentation by Efectis in 2024, where it is mentioned that the gap distance between the roof surface and BAPV modules should mirror how the PV modules are installed [69, N. 3 hours into video]. Thus, the modified test can be conducted with East/West- and South-facing PV modules, in addition the roof parallel PV modules illustrated in Figure 4.

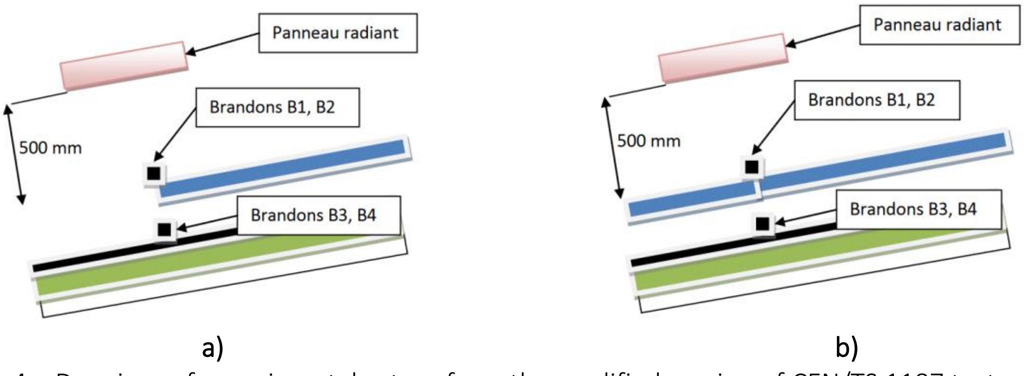

Figure 4 – Drawings of experimental set-up from the modified version of CEN/TS 1187 test method 3.
From: *"Justification des produits photovoltaïques installés en toiture vis-à-vis du feu extérieur"* (2021), CSTB [68].

The increased distance and the shading of radiative heat transfer reduce the concentration of combustible pyrolysis gases released from the tested roof surface. As a result, the probability of self-sustained flame spread decreases, as fire brands (Brandons B3, B4 in Figure 4) are less likely to ignite the pyrolysis gases.
The impact of increased shading is particularly pronounced in the modified test setup illustrated in Figure 4b, which effectively tests the PV modules' response to external fire rather than the combined effect of the roof construction and PV module.

The reduced radiative heat transfer in the proposed modified version of CEN/TS 1187 test method 3 essentially makes it a less stringent test than the original version. As a result, roof surfaces tested below PV modules could achieve a better classification than the same roof surface tested without PV modules. Therefore, the proposed modification of CEN/TS 1187 test method 3 is not considered sufficient to replicate the flame spread scenario that occurs when PV modules facilitate flame propagation in the cavity beneath them.

Despite the theoretical limitations of the modified test method, images from a test conducted in accordance with it [69, N. 3 hours into video] demonstrate that flame spread can occur in the cavity between the PV module and roof surface when testing a configuration similar to Figure 4a. Thus, the modified test method can quantify flame spread within the cavity and assess damage to the underlying roof construction, even with reduced radiative heat transfer to a smaller roof area.

As such, the modified version of CEN/TS 1187 test method 3 shows some potential in assessing the impact of the altered fire dynamics on the roof surface, facilitated by the geometry of the cavity between the PV module and roof surface. Based on the available knowledge, the modified test method has some limitations due to the increased distance between the radiant panel and roof surface. As a result, the outcomes of the current test may not accurately replicate those obtained with more realistic large-scale tests of similar set-ups.

4.3. Tests based on other test methods

Besides the large-scale tests and the modified CEN/TS 1187 test methods, three test methods are introduced. A test method by FM approvals, and Test Report introduced by European Committee for Electrotechnical Standardization (CENELEC) as well as a test method developed in Italy.

4.3.1. Test method by FM Approvals

Similar to the modified European test methods, FM Approvals introduced a modified version of ASTM E-108 in their standard 4478 [70]. Contrary to the European test methods, which in general examines the roofs reaction to fire when exposed to fire brands and/or radiation, ASTM E-108 examines both intermittent flame spread from fire brands [71, Sec. 8] and spread of flame [71, Sec. 9].

The modified test method described in FM 4478 is based on the later (Class A), in which the flame spread length along a roof construction is examined based on ignition with a wind aided line burner which, most likely, emulate a fire plume exiting a window. The test method is a system test which includes the roof covering, PV modules and mounting system. The PV modules should be installed in the desired geometry (East/West, South or parallel to the roof) and a minimum of two panels should be installed along the roof surface. The acceptance criteria are based on flame spread length along the roof covering and PV modules and thus, the test is a pass/fail test [70].

4.3.2. Tests associated with CENELEC

Two test methods are suggested, or accepted, within Europe to examine the combination of BAPV modules and the subjacent roof construction: i) a method suggested in a test report from CENELEC [64] and ii) the test method described in CEI TS 82-89

In 2016, CENELEC published the technical report CLC/TR 50670:2016, *External Fire Exposure to Roofs in Combination with Photovoltaic (PV) Arrays – Test Method(s)*, which outlines a test procedure for BAPV modules on both flat and inclined roofs.
The gas burner developed during the work discussed in section 4.2.1 serves as the ignition source, with a heat

release rate (HRR) of 15 kW. For inclined roofs (45°), the PV module is mounted parallel to the subjacent test deck at a distance of 150 mm. On flat roofs, the PV module is installed at an inclination between 38° and parallel, with a 150 mm gap between its lower edge and the test deck.
The gas burner is positioned 120 mm from the lowest edge of the PV module and either 10 mm or 80 mm above the roof deck. Regardless of roof orientation, the PV module is tested in portrait orientation, with its inclination determined by the height difference between its two shorter sides.
The test evaluates flame spread along or burn-through of the PV module, as well as the presence of burning droplets. However, no classification criteria are defined for burning droplets.

Despite the test report's title suggesting that a PV module is tested in combination with a roof—implying a system-level assessment—the test solely evaluates the performance of the PV module itself. This is because the test deck beneath the PV module is defined as an inert surface. As a result, the test does not account for key parameters such as flame spread along the roof construction, damage to the subjacent roof, or the influence of cavity geometry between the PV module and the roof surface, as described in Section 3. Instead, it focuses solely on the PV module as a product rather than on the fire dynamics of the BAPV system.

In contrast, CEI TS 82-89 acknowledges the importance of testing the PV module in combination with the roof construction. While it adopts the overall test setup, PV module-to-roof distances, and gas burner positioning from CLC/TR 50670:2016, it replaces the inert surface with a roof mock-up. To accommodate a smaller test setup, the PV module dimensions are reduced to 600 mm × 800 mm to fit within a sample holder. Additionally, the gas burner's heat release rate is increased from 15 kW (as specified in CLC/TR 50670:2016) to 30 kW, while the test duration remains 10 minutes. The performance of the combined PV module and roof system is quantified through total heat release, measured via oxygen calorimetry as defined by Janssen [72].

From images and videos of the test method [69], [73], it is observed that the flame from the gas burner penetrates the PV module during the test. Theis occurs because the tempered glass at the front of the PV module shatters when the dimensions of the module are altered to fit the sample holder. As a result, the test method does not assess the modified fire dynamics in the cavity between the PV module and roof surface, nor does it evaluate flame spread along the roof surface.

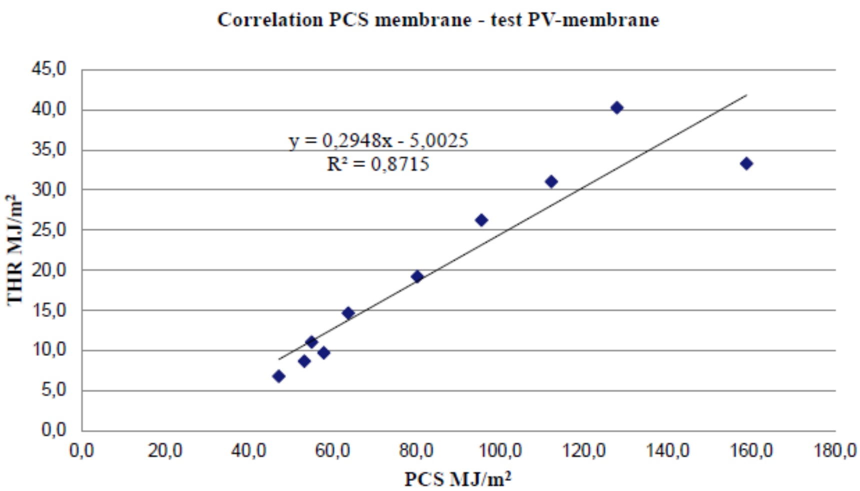

Figure 5 – Correlation between Total Heat Release (THR) on y-axis and Heat of Combustion (PCS) of the tested roofing membranes on x-axis. The different roofing membranes were all tested with a UNI 9174 class 2 module and in accordance with CEI TS 82-89. From presentation by Fabio Parolini [74]

What the test method does assess is the magnitude of energy in the roof construction, as observed in the plot in Figure 3. This plot shows the total heat release (THR) rate from tests conducted with different roofing membranes in combination with Class II PV modules (in accordance with UNI 9174), as described in CEI TS 82-89. The THR obtained in the tests are plotted against the heat of combustion of the tested membranes [74]. It is unclear whether the data points in Figure 5 represent the average of repeated tests. If so, the gradient of the linear regression indicates a convective combustion efficiency of 29.5%, which is significantly lower than the generally accepted combustion efficiency of 60% to 70% for fuels with sooty flames [16]. The most likely reason for this is that the THR quantified in the test originates from the area of the roof sample ignited by the gas burner, not the entire roof sample. Therefore, it is assumed that the THR measured by the test method correlates with both the heat of combustion of the tested roofing membrane and the areal percentage of the membrane that was ignited.

To summarize, neither of the two test methods assesses how the introduction of a cavity between the roof surface and the PV module alters the fire dynamics on the roof. They also do not evaluate the influence of cavity geometry or flame spread caused by re-radiation. Consequently, these test methods do not determine whether the *top event* in the Bow Tie model, a competent ignition source, can escalate into the *major accident event*s: flame spread along the roof and flame spread into the building.

4.4. Partial conclusion

Based on the parameters discussed in section 3, the eight test methods presented in sections 4.1 to 4.3 can be evaluated with respect to their ability to assess the potential consequences of a PV-related fire on a roof construction. The evaluation in Table 2 are based on the four input parameters discussed in section 3.3.3, where the roof construction built-up and cavity geometry were prioritized as the most critical input parameters. In comparison, the PV module type and wind load were considered of secondary importance, tied at a shared third place. In addition to the input parameters, the test methods ability to assess the *top event*s potential of developing into the two *major accident event*s is also evaluated.

Table 2 – Assessment of test methods based on input parameters (prioritized from 1 to 3) and their effectiveness in evaluating potential major accident events (MAEs): flame spread along the roof and into the subjacent fire compartment. Symbols: ✓ = variable included or MAE assessed; X = not included or not assessed; NA = not included or not assessed, but potentially feasible; (✓) = included or assessed, with limitations.

	1 - Roof construction:	2 - Cavity geometry:	3 - Wind load:	3 - PV module:	MAE 1:	MAE 2:
Large-scale test:	✓	✓	X	✓	✓	✓
Red. Large-scale:	✓	✓	X	✓	(✓)	(✓)
Based on CEN/TS 1187:						
Test method 1:	✓	(✓)	X	✓	(✓)	(✓)
Test method 2:	(✓)	(✓)	✓	X	✓	*NA*
Test method 3:	✓	✓	✓	✓	✓	*NA*
Based on other test methods:						
FM 4478:	X	✓	✓	✓	✓	X
CLC/TR 5060:	X	X	X	✓	X	X
CEI TS 82-89:	✓	X	X	((✓))	X	X

Based on the presented research and available test data, large-scale tests are currently the only test methods considered adequate to address both *major accident events*: flame spread along the roof and flame spread into the subjacent fire compartment. Additionally, the reduced large-scale test employing a single PV module has the potential to quantify the same consequences as the full-scale tests. However, no research currently evaluates the comparability between these two test methods.

The similarities between the reduced large-scale test and the modified CEN/TS 1187 Test Method 1 are notable. Although the latter did not consider the influence of cavity geometry when designed in 2013, it should be possible to incorporate this aspect. Thus, the primary difference between the test methods lies in the ignition source, which will be discussed further at the end of the report.

Evaluation of a modified CEN/TS 1187 Test Method 2 is currently based on very limited research, but the limited dimensions of the original test method does limit the modification options of the cavity geometry and well the usage of genuine PV modules. Thus, the potential of developing a system test evaluating the performance of a specific combination of roof construction, cavity geometry and PV module is not possible.

The modified CEN/TS 1187 Test Method 3 is the only test method that considers all four input parameters and evaluates flame spread within the cavity between the roof surface and the PV module. However, it remains unclear whether the method also evaluates flame spread into the fire compartment. Notably, the modification of the original test configuration significantly reduces the severity of the ignition source, due to both the increased distance and the presence of a PV module between the radiant panel and the roof surface, as discussed in section 4.2.3, which theoretically renders the modified test method less strict than the non-modified test method.

The test procedure outlined in FM 4478 does evaluate flame spread along the roof, but it only considers the upper surface of the roof construction and not the full roof build-up. Consequently, the method does not accommodate the inclusion of mitigation strategies such as intermediate mitigation layers. Since the test is structured as a binary pass/fail protocol, the omission of MAE 2 as a criterion may be accepted, given that flame spread along the roof is a prerequisite for flame spread into the building.

Finally, neither of the two test methods based on CLC/TR 5060 are considered adequate for determining whether a specific combination of roof construction and PV module reduces the probability of the *top event* progressing into one of the two *major accident events* - flame spread along the roof surface or flame spread into the roof construction.

5. DISCUSSION OF PARAMETERS – OUTLINE OF TEST METHOD

Based the presented research and discussion of test methods which are being used, developed or accepted within some regulatory systems, a discrepancy is observed regarding the parameters which can affect and assess the potential consequences of a PV-related fire for roof constructions with building applied PV systems.

This final section of the report discusses these parameters and presents an outline of a test method by evaluating if and how the influence of the individual parameters can be varied or assessed. However, the section does not present a test method per se, as such method cannot solely be based on a desktop review but a larger test campaign.

Finally, the large-scale tests are not suggested as a test method as it should be possible to access the likelihood of the two *major accident events* in a smaller scale. The parameters in Table 2 will serve as the focal point of the discussion and finally, the influence of the ignition source will be discussed.

5.1. Parameters which should be assessed

With the major accident events representing the undesired consequences of am PV-related fire, the likelihood of the *top event* progressing into either self-sustained flame spread along the roof (MAE 1) or flame spread into the subjacent fire compartment (MAE 2) should ideally be evaluated in a test method.

As MAE 1 is a prerequisite for MAE 2, a binary pass/fail test method could be based solely on the initial event. However, a pass/fail test method based on whether the fire propagates beyond the ignition source's domain would need to be highly conservative. This is because research indicates that both the gap height and the ignition source are critical parameters, and even minor changes can lead to significantly different test outcomes.

Although flame spread along the roof surface is considered an undesirable consequence, partial acceptance of MAE 1 could facilitate a test system with two pass classifications: a) no flame spread along the roof, and b) no flame spread into the subjacent fire compartment. This approach draws parallels to test methods assessing resistance to fire which requires a redefined understanding of the cavity between the roof surface and the PV module as a fire compartment rather than part of the building envelope. However, such approach aligns with requirements related to the dimensions of PV arrays, which already constitutes compartmentation to prevent self-sustained flame spread from one PV array to another. In addition, a test method based on both *major accident events* would introduce a level of redundancy, as it limits the probability of MAE 1 evolving to MAE 2, even if the probability of flame spread along the roof is limited.

As such, it is concluded that a test method should be able to assess both *major accident events*.

5.2. Input parameters

From a standard test perspective, designing a test method where all four input parameters in Table 2 are treated as variables would introduce a level of complexity that does not necessarily yield more accurate or reproducible results. Due to the sensitivity of the fire dynamic system comprised of the roof construction, the PV modules, and the geometry between the elements of the system, it is suggested that variation of some input parameters be either limited or fixed.

5.2.1. Roof construction

Given that flame spread along and into the roof construction are the primary parameters assessed, the roof assembly should be considered the key variable and, consequently, the component to receive classification. Testing only the roof covering would limit the assessment to flame spread along the roof surface. Therefore, it is recommended to test the combination of the roof covering with the subjacent roof build-up. While testing the full roof build-up, including roofing membrane, insulation materials, vapor barrier, load-bearing components, and potential mitigation barriers, introduces a vast number of material combinations, it is suggested to focus on the specific combination of roofing membrane, insulation material, and potential mitigation barrier.

Finally, it is crucial that the dimensions of the examined roof construction allow for the assessment of self-sustained flame spread beyond the domain of the ignition source. Without this, the evaluation would be limited to determining whether the ignition source can propagate into the roof build-up. This does not represent a genuine *consequence* of a PV-related fire, where the fire-related risk is attributed to the potential *consequences* rather than the *top event* - a competent ignition source.

5.2.2. Cavity geometry

With the gap height between the roof surface and the PV module being a critical parameter, as discussed in subsection 3.1.1, it can be a decisive factor between "flame spread" and "no flame spread." Additionally, it has been found that lower gap heights result in higher heat transfer toward the roof construction beneath the roof surface. Therefore, it is essential that the gap between the PV module and the roof surface corresponds to the gap heights observed in BAPV mounting systems, since a lack hereof would prevent adequate evaluation of the parameters which be assessed according to section 5.1.

With the cavity geometry defined by both the gap height and the inclination of the PV modules, a vast number of cavity configurations exist. However, the research presented in section 3.1.1 indicates that the gap height at the location of the ignition source is a more decisive factor than the inclination. Additionally, the research has shown that lower gap heights result in higher heat transfer toward the roof construction beneath the roof surface. Thus, tests conducted with low gap heights and no inclination, would represent a more conservative test scenario than tests conducted with an inclination, which, in accordance with the research presented in subsection 3.1.1 would also require a larger test deck.

For these reasons, it is essential that the gap height between the PV module and the roof surface reflects the low gap heights typical of most BAPV mounting systems. In a test method, this could be defined as a fixed gap height low. Finally, variation of inclination results in an increased complexity of the test method and for that reason, it suggested to only test with PV modules parallel to the roof surface. It is acknowledged that such an approach would make the test stricter, but it is also expected that a more severe test method would result in a greater variation in outcomes in the form of heat transfer to the materials beneath the roof surface.

5.2.3. The use of PV modules

As discussed in subsection 3.1.3, current research does not demonstrate that the fuel load associated with PV modules, based on existing technology, is a decisive factor in significantly increasing the severity of a PV-related fire. In contrast, the cavity geometry has been shown to have a more substantial impact on fire severity as discussed in subsection 5.2.2.

Based on the current level of knowledge, combined with the constant stream of new PV modules on the marked, system tests based on a specific PV module model from a specific manufacturer is not considered viable and thus, it is suggested to test with an inert PV module substitute. It is acknowledged that such an approach necessitates an additional test method to assess whether the fuel load attributed to a given PV module exceeds an acceptable threshold value, and the additional complexity associated with introduction of separate test method might be undesirable.

5.2.4. Wind load

The influence of wind load in combination with BAPV -9systems on roof constructions is currently not well understood. Therefore, further research is needed to determine whether the introduction of wind load would result in a more severe flame spread scenario. If this is the case, it is suggested to incorporate such wind load into testing protocols.

5.2.5. Ignition source

Finally, it is acknowledged that the type and severity of the ignition source in a test method assessing the consequences of a PV-related fire have not received much attention within this report. The reason for this is that the ignition source within such a test method represents the *top event* of the bow tie model, which is solely defined as a competent ignition source. Thus, the cause of the *top event* being triggered relies on the evaluation of *threats* in the fault tree analysis, from which the most severe but probable ignition source should be determined and replaced by an adequate substitute in the test method.

Based on this, a competent ignition source associated with an electrotechnical failure in one of the components discussed in section 2.1 does not necessarily represent the most severe ignition scenario. Other threats, such as burning brands or radiation from a nearby fire, may lead to more severe consequences. Failure to identify the most severe competent ignition source will result in a test method that does not adequately address the consequences.

As such, that the ignition source in a test method should represent the most severe competent ignition source. However, it should be emphasised that the domain of the ignition source should not exceed the area of the examined roof construction, as such ignition source would render evaluation of the consequences impossible. Based on the current state of knowledge, the ignition sources employed in the large-scale test, the reduced large-scale test, the test method based on CEN/TS 1187 Test Method 1, and the method defined in FM 4478 are all considered adequate.

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