PHASE I NOTE

SOL-IGNIS

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Fire Testing of Roof- Mounted Solar Panels

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Note: The Phase I note constitutes the initial report, which includes only an introduction to the topic, a discussion of relevant parameters, and the preliminary design of the experimental set-ups. Accordingly, this document does not represent the final report, which will be published medio 2026.

CONTENT

1. INTRODUCTION

The implementation of photovoltaic (PV) systems into the built environment is a central component of Europe's strategy for achieving a green energy transition and reducing reliance on fossil fuels [1]. However, several recent fire incidents involving rooftop PV systems, such as those at IKEA facilities [2–4], the Miramar shopping centre in Spain [5], a school in Belgium [6], and two separate events in Germany [7], have highlighted emerging fire safety challenges associated with these installations.

Existing European fire classification methods for roof constructions EN 13501-5 [9], were developed without consideration for the altered fire dynamics that result from building-applied photovoltaic (BAPV) systems. When PV modules are installed, they form a cavity between the module and the roof surface. This configuration can promote deflected flames and increase radiative heat transfer. In some cases, it can also enable self-sustained flame spread, even when the underlying roofing system has received the highest classification.

This document presents a pre-normative study that examines whether CEN/TS 1187 Test 2 can be modified to represent these altered fire conditions more accurately. The aim is to examine if a revised test method can reliably assess both flame spread and thermal exposure to the underlying insulation layer in, primarily flat, roof constructions with building applied PV systems.

The SOL-IGNIS project, led by DBI – The Danish Institute of Fire and Security, builds on prior research including large-scale experiments incorporates technical knowledge from both the scientific literature and real-world case data. The work described in this Phase I note includes a combined experimental campaign involving large-scale roof mock-ups and a modified medium-scale version of CEN/TS 1187 Test 2.

The campaign focuses on how design parameters such as roof coverings, insulation types, and cavity geometry, as well as ambient conditions and ignition scenarios, influence fire behaviour in PV-integrated roof systems. The overall objective is to determine whether a modified version of CEN/TS 1187 Test 2 can be developed into a reliable and representative testing methodology. Such a method would support future standardisation efforts and ensure that fire safety keeps pace with the increasing deployment of PV systems across Europe.

This document serves as an initial note which briefly define the basis of the experimental campaign, test set-ups and instrumentation. The document does not yet contain the outcome of the project.

2. BRIEF SUMMARY OF CURRENT KNOWLEDGE

2.1. Consequences of PV-related fires

With an increased focus on the fire-related risk associated with the introduction of the PV-technology into the built environment, research has been carried out at various scales. Inspired by Kristensen and Jomaas large-scale tests conducted in 2016 [10], commercial companies and industry associations have conducted large-scale tests on roof mock-ups [11–14], whereas non-commercial research have examined the influence of parameters that have the potential to affect the consequences of a PV-related fire.

In general, the introduction of a PV module modifies the fire dynamics whereupon self-sustained flame spread can occur in the cavity between the roof surface and the backside of the PV module [15]. For that reason, the introduction of PV modules facilitates flame spread along roof constructions with roofing membranes that are compliant with the requirements in the Danish building regulations, i.e., classified B_{ROOF}(t2) in accordance with EN 13501-5 [9] and CEN/TS 1187 test method 2 [10].

Figure 1 illustrates the ignition process on a conventional flat roof construction compliant with the building regulations [15]. After ignition of the wood crib, often used as an ignition source in tests/experiments [16], conductivity and mostly radiation from the flame heats up the roof surface within the domain of the ignition source. As the temperature of the roofing membrane, often posed by a bituminous roofing felt or single-ply plastic-based membrane, increase, the material releases combustible pyrolysis gases. Ignition of the roof surface occur when the concentration of these gases exceeds their lower flammability limit (LFL) [17], after which the radiation from the flames of the ignited membrane, in combination with the radiation from the wood crib, increase the temperature near the newly formed flame front (Figure 1d).

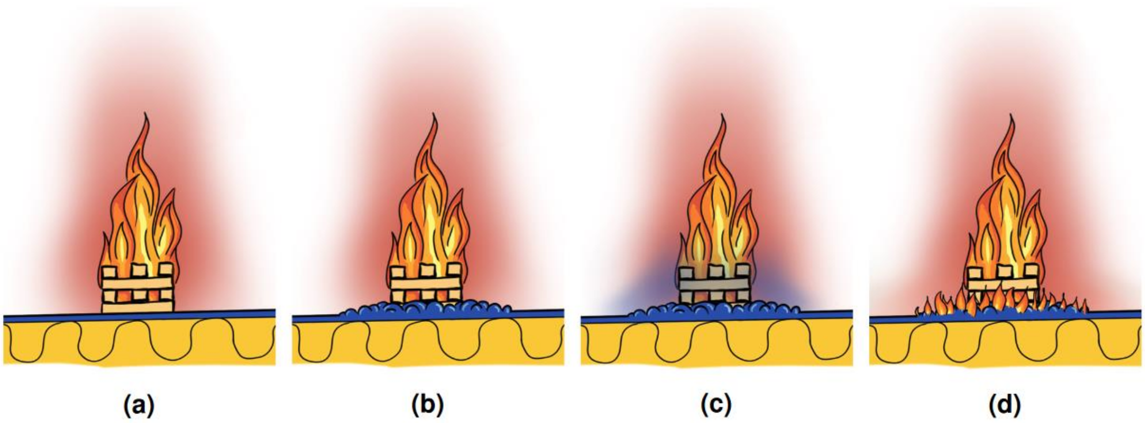

Figure 1 – Sketched ignition process of roof construction (blue roofing membrane, yellow insulation) with wood crib. a) Radiative heat transfer from ignited wood crib (fading red cloud), b) Heat of nearby roofing membrane, c) Release of combustible pyrolysis gases (fading blue cloud), d) Ignition of pyrolysis gases, addition radiative heat transfer, but no self-sustained flame spread. From: J.S. Kristensen (2022) [15].

If the combined radiation from the wood crib and the ignited roof surface is sufficient to elevate the temperature of the unignited material ahead of the flame front, pyrolysis gases will be released in concentrations beyond the lower flammability limit (LFL). As a result, the flame front will propagate further away from the domain of the initial ignition source. Due to the relatively low view factor[1] between two perpendicular surfaces [7], the radiative heat transfer from the vertical flame towards a given point on the horizontal roof surface, reduces significantly as the distance between ignition source and point increase [8]. Thus, continuous flame spread along the roof surface outside the domain of the ignition source, is only possible if the heat transfer from the existing pyrolysis zone, and flame front, exceeds the energy required to elevate the temperature of the virgin material ahead of the flame front sufficiently [20].

For roof surfaces compliant with the requirements in the Danish Building regulations, the classification B_{ROOF}(t2) ensures that no self-sustained flame spread will occur along the roof surface, which is essential to prevent flame spread along the building envelope – an event that would breach a fundamental part of all fire safety strategies [21].

[1] *View factor* is also known as *configuration factor*.

However, the installation of a building applied PV systems introduce a cavity between the roof surface and the backside of the PV modules which deflects the flame from the initial ignition source as illustrated in Figure 2. The deflection of the flame alters the view factor and renders the flame spread scenario near-concurrent, which results in a significant increase in the radiative heat transfer towards the surface below the most elevated part of the inclined PV module [22].

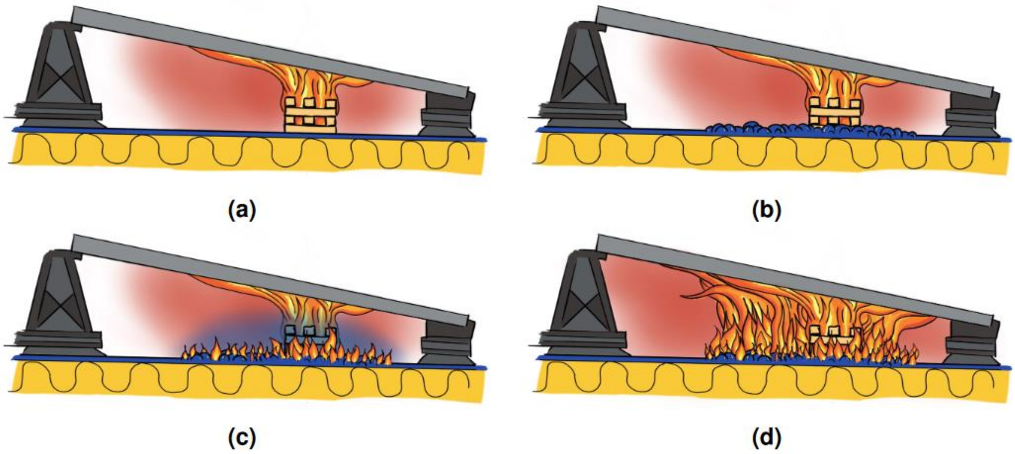

Figure 2 – Sketched ignition process of roof construction (blue roofing membrane, yellow insulation) with wood crib below BAPV module. a) Radiative heat transfer from deflected flame (fading red cloud), b) Heat of nearby roofing membrane, c) Release of combustible pyrolysis gases and initial ignition (fading blue cloud), d) High heat release rate due to higher concentration of pyrolysis gases, heating nearby materials and self-sustained flame spread. From: J.S. Kristensen (2022) [15].

Large-scale tests have demonstrated that the increased view factor between the roof surface and the flame deflected below the PV module does enable selfsustained flame spread [11–14]. In case of self-sustained flame spread, it is essential from a fire safety strategy perspective that the fire does not evolve even further and propagates into the subjacent building. As such, the introduction of a BAPV system on roof construction increase the potential consequences from i) *flame spread along the building,* to also include ii) *flame spread into the building.* Consequently, it is necessary to examine how the consequences can be mitigated in case of a PV related fire.

Material, geometric and ambient parameters have been studied to understand why the self-sustained flame spread occur and thus, how the severity of PV-related fires can be reduced to an acceptable level by introducing mitigation measures. For BAPV systems on industrial or commercial flat roof constructions, the parameters affecting the consequences can be divided into three design parameters and two ambient variables, with design parameters being parameters that can be modified or engineered consciously, contrary the ambient variables, wind and temperature.

In the following section, the influence of the design parameters is discussed in brief, followed by a discussion of the ambient variables in subsection 2.3 .

2.2. Design Parameters

2.2.1. Mounting system – gap height and inclination

BAPV modules are installed on roofs using mounting systems which are either ballasted, glued, or mechanically fixed to the roof. This results in a geometry where the module creates a cavity between the module and roof as briefly discussed section 2.1. As such, the mounting system serves as both a potential fuel load and critical component of the BAPV system which determines the geometry of the cavity between the roof surface and backside of the PV modules. The cavity is defined by the gap height between the backside of the PV module and the inclination of the module.

Experimental work of flame spread along the reference material[2] polymethyl methacrylate (PMMA) identified a critical gap height between the roof surface and a parallel horizontal inert barrier of stainless steel, or a PV module [25]. Slow steady state flame spread was observed along the PMMA for gap heights above the critical gap height, whereas the initial slow flame spread transitioned into a rapidly accelerating flame front for gap heights below the critical gap height [25]. Similar observations were found, when the PMMA was replaced by small roof construction mock-ups with a PVC-based single-ply roof covering compliant with British building regulations (B_{ROOF}(t4)) [26]. However, a binary flame spread scenario was seen in the tests on the roof mock-ups. Thus, no flame spread outside the domain of the ignition source was observed in the baseline tests with no cavity and in tests with gap heights above the critical gap height, whereas flame spread along the full roof mock-up was seen in test with a gap height below the critical gap height [26].

The findings in the flame spread studies align with a series of steady state experiments examining re-radiation from a gas burner below horizontal and inclined surfaces [22, 27, 28]. For inclined surfaces, the highest radiative heat flux is measured below the most elevated part of module the near the gas burner due to a buoyancy driven increased upward gas flow, thus flame extension, as illustrated in Figure 2. However, increased inclination leads to a reduced view factor between the most elevated part of the PV module and roof surface. Consequently, the effect of inclinations above 10° is not expected to increase the heat flux significantly more.

To conclude, the cavity geometry, and especially the gap height between the back of the PV module and the surface of the roof construction, can serve as a decisive factor that differentiates flame spread from no flame spread. The conclusion is based on tests conducted with a reproducible ignition source which will be discussed further in section 3.

In the Norh European countries, most BAPV modules are installed in East/West orientated configuration or parallel with the roof surface with inclinations between 0° and 15°, but systems with higher inclinations are used in areas with significant snowfall during winter.

2.2.2. PV modules

The majority of photovoltaic (PV) modules are composed of a technology were the cells are made of the inert material crystalline silicon (c-Si), which represented an unquantified majority of the production in 2007 [29] and 98% of the added capacity in 2024 [30]. A transparent front sheet, often tempered glass, are used in all c-Si PV modules and behind the front sheet, the PV cells are encapsulated between two layers of a transparent polymer, such as ethyl vinyl acetate (EVA) [31], and a backing material in the form of glass or, more commonly,

[2] PMMA is often used as reference material for fundamental flame spread studies [23, 24].

a plastic foil backsheet. Depending on the type of backsheet, the module types are referred to as glass/glass or glass/foil.

Despite the increased fuel load ascribed to the encapsulant and plastic backsheet, no published research indicates 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 [32].

No significant difference was observed in the flame spread tests along the PMMA when tests were conducted with respectively glass/foil modules and an inert stainless-steel board [25], whereas a small difference in flame spread length were observed when stainless steel-board and PV modules was tested above a PVC-based single ply membrane on the roof mock-ups [26]. However, no self-sustained flame spread occurred along any of the PV modules used for the test, which indicates that the modules should be considered a limited fuel load in the initial flame spread phase. Consequently, it can be concluded that fuel load of the examined glass/foil modules have a limited contribution to the modified fire dynamic system, when compared to the influence of other parameters, such as the increased re-radiation facilitated a gap height reduction.

It is expected that the limited fuel load contribution to from the backsheet can be ascribed to thermal properties of the backsheet material which is often a fluropolymer or polyvinyl fluoride that is hard to thermally degrade [33]. It is acknowledged that not all plastic backsheets of glass/foil modules are fluorinated, so additional research examining the various backsheets energy contribution is needed before any solid conclusions can be made. It is acknowledged that the encapsulant of the PV modules does represent a fuel load due, which might affect the overall consequences of a PV related fire as it can contribute to the fire if the plastic or glass backsheet of the modules are breached. However, thermal degradation of the backseet is not expected during the initial flame spread phase of a PV-related fire and since the experimental work within this pre-normative work is based on the current knowledge, it is assumed that the fuel load contribution from glass/foil modules is near insignificant.

2.2.3. Roof construction

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

Essentially, the roof build-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 constructions, but no known research have studied the influence of these during PV-related fires. In addition, no known work has systematically examined the influence of the roof surface below PV modules.

However, examination, or comparison, of the temperature development in materials below the roofing membrane has been the focal point of all large-scale tests. Kristensen and Jomaas examined if mitigation layers of mineral wool or PIR insulation could protect a subjacent EPS-insulated roof construction [10], whereas PU Europe and Kingspan compared the performance of PIR insulation with mineral wool [11, 12]. Finally, the European Manufactures of Expanded Polystyrene, EUMEPS, examined if either two layers of glass fibre fleece or 12 mm cement fibre board could protect the subjacent layer of EPS [13, 14]. In Kristensen and Jomass test with a mitigation layer of 50 mm thick PIR insulation, the wood crib used for ignition penetrated the mitigation layer after 60 minutes, whereupon self-sustained flame spread occurred within the EPS [10]. Ignition of the

EPS also occurred in EUMEPS tests conducted with a mitigation layer of glass fleece [13]. Otherwise, the fire solely propagated below the PV array in all tests, besides the test conducted with a cement fibre board where the flames only propagated below one of the four PV modules. All large-scale tests were conducted with PVC-based single-ply membranes.

As such, the large-scale tests illustrates that the roof constructions insulation material, or a mitigation layer between the roofing membrane and subjacent insulation material, can serve as barrier which potentially can prevent flame spread along the roof and into the building.

When examining scaled down roof construction mock-ups, it was found that the heat transfer towards the subjacent roof construction increased with a reduction of the gap height between the backside of the PV module and the roof surface. The temperature occurred for two reasons: i) Increased heat transfer during the pre-heating phase, and ii) slower flame spread in the tests conducted with the lowest gap height due poor combustion efficiency, thus increased heat transfer from the pyrolysis zone toward the subjacent insulation [26].

As such, it can be concluded that the fuel load ascribed to the roofing membrane below the BAPV modules can also serve as a decisive factor.

2.3. Ambient variables

2.3.1. Wind load

Wind load affects the way flames develop and spread on horizontal roof surfaces. Depending on the direction of the wind relative to the flame front, it can either accelerate or hinder flame propagation which is also defined as concurrent or opposed flame spread [23]. During concurrent flame spread, the flame front is deflected towards the preheating zone which increase the view factor and thus radiative transfer from the flame, which increases the flame spread rate. For opposed flame spread, the flame spread rate is reduced as the view factor between flame front and pre-heating zone increase [20].

During the ignition phase, higher wind loads can dilute the concentration of combustible pyrolysis gases to levels below the lower flammability limit, preventing ignition and subsequent flame spread outside the domain of the ignition source [15]. Regardless of the wind load, the flame is being deflected within the cavity under the PV modules, which renders the flame spread scenario semi-concurrent no matter the wind direction on a roof construction with PV modules.

Consequently, it is acknowledged that the wind load can affect the initial ignition process and can inhibit self-sustained flame spread, but in case of self-sustained flame spread it is not expected that the wind load will have a significant effect on the flame spread rate due to the presence of the cavity [15].

2.3.2. Ambient temperature

Higher ambient temperatures reduce the energy required to bring combustible materials up to their ignition point. When the surrounding air is already warm, the preheating phase before ignition is shorter, allowing flames to develop and spread more quickly. This effect is particularly relevant for materials with relatively high ignition temperatures, as the thermal gap between ambient conditions and ignition is smaller. As a result, elevated ambient temperatures contribute to faster flame spread once an ignition source is present.

3. IGNITION SOURCE

For PV-related fires in the built environment, the initial fire in the form a competent ignition source can be the outcome of various events which have occurred individually or combined with each other. The term *competent ignition source* is used within fire safety investigation and is defined 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"* by the National Institute of Standards and Technology (NIST) [34].

Research have illustrated that events leading to the formation of a competent ignition source can originate from both components of the PV system itself as well external ignition sources not related to the PV system [35]. A study by Mohd Nizam Ong et al. [35], based on data from Australia, Germany, and the UK, indicates that around 2/3 of the examined PV-related fires are caused by failure of a PV component. In the Netherlands, 152 PV-related fires have been identified between November 2022 and October 2023, from where detailed information was available for 70 of the incidents and the fire occurred in a component of the PV system in 30 cases. In 29 incidents, the fire was not caused by the PV system and the cause of the fire could not be identified in the remaining 11 cases, which leads to the conclusion that there is an equal likelihood of the fire originating within and outside the PV system [36]. In both studies, it is acknowledged that, that the conclusions are based on limited data and that more research is needed to draw final conclusions.

Despite the uncertainty associated with both studies, they do indicate that the introduction of the PV technology into the built environment does introduce additional ignition sources in addition to the limited types of ignition sources already present. Consequently, the definition of the competent ignition should be reconsidered when developing tests for roof constructions in combination with building applied PV systems. When it comes to fires caused by the PV system, the fires are often the result of direct current arcing which can reach temperatures up to 6000 K [37]. However, the use of a DC-arc as an ignition source for fire tests are not suggested as the repeatability and reproducibility relies on many external factors and plastic components of the DC-arc is often ignited as the first nearby fuel as studied by Hastings et al. [38]. As such, ignition of a PV-component, caused by DC-arcing, serves as an additional type of ignition source on roof constructions, in addition to burning brands, radiation from a nearby building fire, or the fire plume from a subjacent compartment fire.

From a testing perspective, the introduction of an additional source of ignition does not necessarily require the introduction of a new ignition source when developing a test method for testing roof constructions in combination with BAPV systems. Depending on the ignition source in the existing test method for roof constructions without a BAPV system, such as test 1-4 in CEN/TS 1187, an ignited component of a PV system might not serve as a more severe ignition source.

4. EXPERIMENTAL CAMPAIGN

As described in the introduction, the experimental campaign consists of two different scales, three large-scale tests and a series of tests where it is examined whether the existing Nordic test method, CEN/TS 1187 Test 2, can be modified so it quantifies the potential consequences of PV related fires. In the following sections, the evaluation criteria for the for the pre-normative tests development will be introduced, followed by the introduction of the key variable and overall roof built-up.

Based on that, the design of the large-scale tests is presented, followed by a presentation of a modified CEN/TS 1187 test method 2 and discussion of input variables. Finally, the test plan is introduced.

4.1. Evaluation criteria

Where the non-modified test method solely address flame spread length along the test sample, the objective of the modified test method is to examine if it can also address thermal exposure from the burning roof surface towards the subjacent insulation material – in case of self-sustained flame spread. Stølen et al. have previously modified CEN/TS 1187 test 2 [39], but their tests solely examined the influence of gap height and two wind loads. Thus, the tests did not examine different membranes nor ignition sources and limited comparison was made to large-scale tests. By examining these additional variables, all potential modifications of the test method have been exhausted and it can be concluded whether a modified test adequately evaluates the potential consequences of a PV-related fire as discussed section 1 and subsection 2.2.3.

The sufficiency of the modified test method should be evaluated on its ability to adequately indicate:

a) self-sustained flame spread along the roof surface.

b) heat transfer from potential flame spread in the cavity to the subjacent insulation material.

Based on the discussion of design parameters, it is found that the thermal parameters ascribed to the roof covering represents a key variable within the fire dynamic system that have the potential to affect the consequences of a PV-related fire. Ideally, no self-sustained occur within the cavity between the backside of the PV module and the roof surface, whereupon heat transfer into the subjacent insulation limited. However, it is acknowledged that PV-related fires do occur as discussed in the Introduction and thus, it is relevant to quantify how the subjacent roof construction is affected in case of that. By doing so, it would be possible to identify roof constructions which, in combination with BAPV systems, would yield less severe consequences and thus be acceptable solutions. The identification of the roof constructions roof covering as a key variable corresponds with the membrane being the component which obtains the classification within the classification system defined in EN 13501-5 [9].

4.2. Overall roof built-up

With the roof covering representing the key variable in the roof construction build-up, the objective of the pre-normative work is to evaluate whether a modified CEN/TS 1187 Test 2 can distinguish between the outcomes of tests conducted on similar roof build-ups incorporating two different roof coverings.

Due to the lack of existing data from large-scale tests conducted in controlled indoor environments, an initial full-scale test will be performed. Data from this test will be used to calibrate a modified version of CEN/TS 1187 Test 2, aiming to replicate the results observed in the large-scale setup.

In both the full-scale and modified test configurations, flame spread length will be quantified, and heat transfer from the cavity to the underlying insulation will be monitored using Type-K thermocouples. Therefore, it is crucial that the overall roof build-up in both test configurations remains as comparable as possible, within the dimensional constraints of the CEN/TS 1187 Test 2 setup.

For the purposes of this study, the roof covering and insulation are considered the primary components defining the roof build-up. While it is acknowledged that a complete roof assembly includes additional layers, the maximum allowable sample thickness of 150 mm in the CEN/TS 1187 Test 2 limits the investigation to the upper layers of the construction.

4.2.1. Roof coverings

With a limitation of three large-scale tests, two roof coverings will be examined, allowing for a single repetition. The tests will be conducted using roof coverings consisting of a bitumen-based roofing felt and a single-ply PVC-based membrane, respectively.

These two product types have been selected due to their distinct thermal characteristics, where the thickness of the roof coverings is particularly significant. The single-ply membrane is considered thermally thin, while the multilayer roofing felt renders the membrane thermally thick [23]. As a result, a uniform temperature distribution is assumed across the single-ply membrane, whereas a temperature gradient is expected between the surface and underside of the roofing felt.

The difference in thermal thickness between the two roof coverings affects both evaluation criteria defined in section 4.1. In the case of the thermally thin single-ply membrane, the thermal properties of the underlying material can significantly influence flame spread. If the subjacent material possesses high specific heat capacity, thermal conductivity, and density, it can act as a heat sink, thereby inhibiting or delaying ignition of the roof covering ahead of the flame front. Conversely, a material with low density, specific heat, and thermal conductivity would limit heat transfer between the roof covering and insulation, leading to faster heating of the roof covering, increased probability of ignition, and faster flame spread [18].

4.2.2. Insulation material

With the roof covering representing the key variable, all remaining parameters in the large-scale tests must remain constant.

It has been decided to perform the tests on roof constructions insulated with mineral wool, as this material is commonly used in the built environment in Denmark. Mineral wool was selected over other insulation materials such as PIR, PUR, or EPS, as the introduction of plastic-based insulation could increase the overall complexity of the experimental campaign. This is primarily due to the potential for deformation of the roof build-up, which would introduce an additional variable that could influence the fire behaviour and overall test outcomes as seen in previous medium- and large-scale tests [10, 13, 26].

4.3. Large-scale tests

With the large-scale tests representing the reference tests for the modified CEN/TS 1187 test 2 (medium-scale), it is decided that they should be conducted similar to previously conducted large-scale tests by other organisations and test institutes. By doing so, it is ensured that the modified medium-scale tests are compared to tests which are generally accepted to evaluate the consequences of BAPV-related fires on flat roof constructions [10–14]. As such, all large-scale tests will be conducted on squared roof mock-ups with side lengths of 6 meters and a small building applied (BAPV) array of four PV modules in an East/West configuration. In the following sections, the roof built-up, PV system, instrumentation and ignition source will be discussed.

4.3.1. Roof mock-up

As concluded in section 4.2, the two different roof constructions tested will be almost similar, with the roof covering being the only exception. As such, the sectional view of all the roof mock-ups will correspond to Figure 3 where only uppermost layer, layer 1, will vary across two tests as indicated by the option in Table 1. Material datasheets of the used construction products can be found in appendix[3]. To prevent material properties of non-homogeneous products, such as bitumen-based roofing felt, from introducing an additional variable to the tests, it is ensured that the upper bitumen layer and the flame barrier are from the same batch.

Table 1 – Overview of the layers in accordance with the sectional view in Figure 3. **Note:** *Material datasheets of the specific products can be found in appendix of the final report.*

Layer	Component	Product	Thickness	Mass
1	Upper bitumen layer	Katepal PF 5500 SBS	4.3 mm	5.5 kg/m²
	Flame barrier	Katepal K-MS 170/4000 SBS	3.1 mm	4.0 kg/m²
	OR			
	PVC membrane	-	-	-
	Glass fleece	-	-	-
2	High density MW	Rockwool TF Plade	20 mm	3.5 kg/m²
3	Lower density MW	Rockwool Dura Underlay	100 mm	13.5 kg/m²
4	Moisture barrier	Katepal PF 3200 SBS	2.2 mm	3.2 kg/m²
5	High density MW	Rockwool Dura Underlay	50 mm	6.5 kg/m²
6	Trapezoidal steel deck	-	-	-

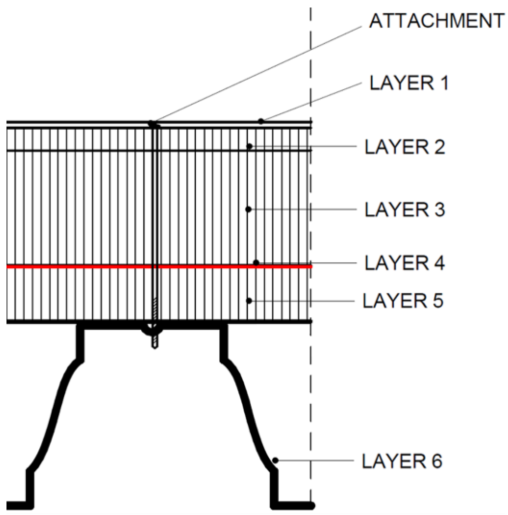

Figure 3 – Sectional view of the roof mock-ups used for the large-scale tests. Layers from top to bottom in accordance with Table 1.

4.3.2. PV array

The Danish branch of the German company BayWa R.E. will supply and install the mounting system and PV modules for three large-scale tests. The small East/West orientated PV array will be ballasted to the roof with the ballast corresponding the required load for installation of such system on the roof construction of DBI's test facilities in Hvidovre, Denmark. The PV modules are installed with the modular mounting system "*Flat roof system III «the shortcut»"* manufactured by the BayWa R.E. owned company Novotegra [40]. Load calculations and dimensions of the small arrays are found in the appendix of the final report, from where the sectional view in Figure 4 also originates.

[3] Material datasheets will be included in the final report.

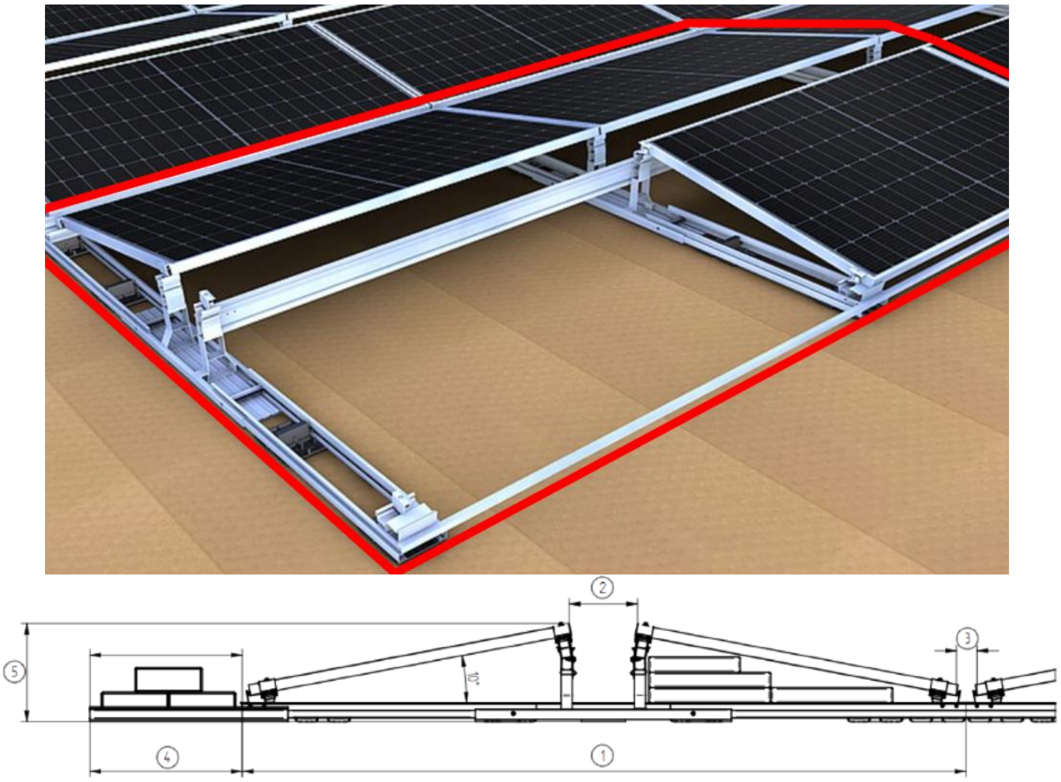

*Figure 4 – **Upper:** Commercial sketch of the mounting system used in the large-scale tests. The area highlighted in red corresponds to the array used in the three large scale tests from: REFRENCE. **Lower:** Sectional side view of the PV mounting system, PV modules and ballast. **Note:** Dimensions will be defined after the first large scale test.*

4.3.3. Ignition source

Similar to most previously conducted large-scale tests, the gas burner specified in CLC/TR 50670 will be used as the ignition source [41]. This gas burner was developed through a test series conducted by TÜV Rheinland, Currenta GmbH, and Bergische Universität Wuppertal [42]. The objective of the series was to design a gas burner capable of replacing the wood wool basket used as the ignition source in CEN/TS 1189 Test 1 when evaluating roof constructions in combination with PV modules.

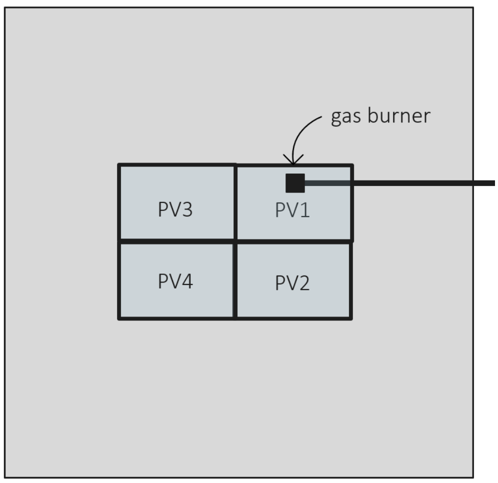

Figure 5 – Top view of the roof surface, PV array and location of gas burner.

It is unclear how the gas burner developed in the German studies came to be included in the CENELEC test report CLC/TR 50670, which, despite its title *External fire exposure to roofs in combination with photovoltaic (PV) arrays – Test method(s)*, does not incorporate any roof construction components and therefore solely evaluates the reaction to fire of the tested PV module.

It is acknowledged that 10 minutes of exposure to a 15 kW gas burner constitutes a significantly more severe ignition source than the wood crib used in CEN/TS 1187 test 2. However, previous large-scale tests have demonstrated that the gas burner is capable of igniting the roofing membrane beneath a single PV module eg. PV1 in Figure 5 [11–13]. Yet, self-sustained flame spread beyond the ignition source, propagating below all four modules, does not always occur, as observed when EUMEPS introduced a 12 mm thick cement fibre board between a single-ply PVC-based roofing membrane and the subjacent layer of EPS insulation [6]. Consequently, the varying outcomes of the large-scale tests conducted with the 15 kW gas burner illustrate that self-sustained flame spread outside the ignition source's domain is a result of the modified fire dynamic system, rather than the ignition source itself.

In addition, the consequences of PV-related fires discussed in the Introduction of the report illustrate the presence of a competent ignition source in the cavity below genuine PV systems. Unlike small- and medium-scale tests, large-scale tests do, to a greater extent, allow the use of more severe ignition sources, as the larger scale enables a clear differentiation between the consequences of the ignition source itself and those of a test sample with distinct characteristics.

In all tests, the square-shaped gas burner was placed at the midpoint of the PV module's width, referred to as PV1, as depicted in Figure 5. The horizontal distance from the burner’s closest edge to the lower edge of the PV module should be 12 cm, and the vertical clearance from the bottom of the burner to the roof construction 8 cm.

4.3.4. Instrumentation

A total of 26 type-K thermocouples will be used to measure the temperature below the roof covering (TC1-TC13) and between the insulation materials in layers 2 and 3 (TC14-TC26) as illustrated in Figure 6. Thermocouples TC1-TC9 are all installed below the PV array to quantify heat transfer from the cavity toward the subjacent insulation material. By installing thermocouples TC14-TC22 directly below TC1-TC9, the heat transfer can be quantified further and will be less prone to temperature fluctuations due caused by radiation from the pyrolysis zone. Five additional thermocouples (TC27-TC31) are installed vertically below TC2, TC4-TC6 and TC8 between layers 3 and 4.

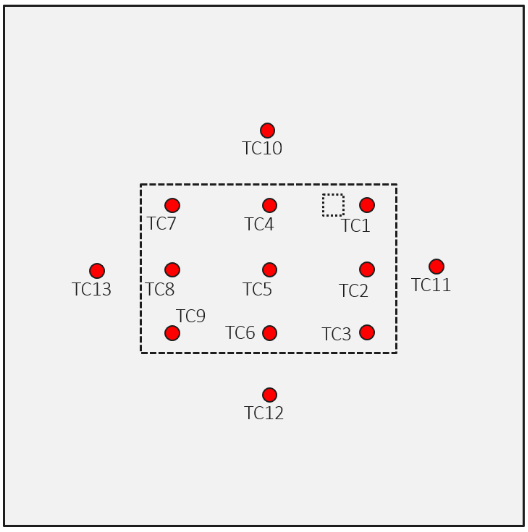

Figure 6 – Location of thermocouples TC1-TC 13 below roof covering. An additional nine thermocouples, TC14-TC22, is located directly below TC1-TC9 between layer 2 and 3. Dotted square indicates location of gas burner.

As limited flame spread have occurred outside the cavity below the PV array in previously conducted large-scale tests [10–14], only four thermocouples (TC10-TC13) are installed below the roof covering.

All tests will be recorded by multiple video cameras. The location of the cameras will be determined after the roof mock-ups are completed. The recordings will solely serve as a visual reference for the analysis of the tests and will not be used for data processing.

4.4. Medium-scale test - modified CEN/TS 1187 test 2

The modified CEN/TS 1187 Test 2, hereafter referred to as the medium-scale test, is based on the initial work conducted by Stølen et al. [39], who introduced a stainless-steel board as a substitute for a PV module above the test deck of CEN/TS 1187 Test 2. In their tests, flame spread was observed along a bitumen-based roofing membrane installed on 22 mm chipboard, with various gap heights ranging from 6 cm to 15cm, in addition to baseline tests conducted without a substitute PV module.

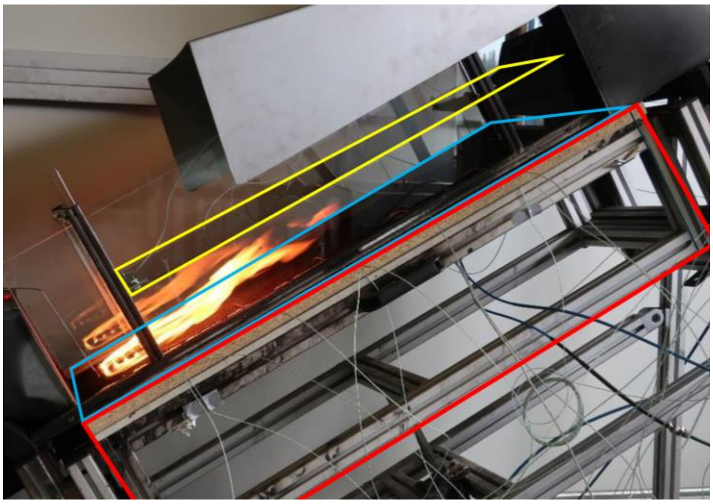

Figure 7 – Edited image from Stølen et al. [39]. Experimental set-up of their modified CEN/TS 1187 test 2. ***Yellow:*** *A stainless-steel board used a substitute for a PV module.* ***Blue:*** *Bitumen-based roofing felt installed on 22 mm chipboard.* ***Red:*** *Volume below the sample surface which can accommodate insulation materials at a maximum depth of 150 mm.*

Through tests conducted using Stølen et al.'s modified setup, illustrated in Figure 7, it was found that only the lowest gap height of 6 cm resulted in a significant increase of flame spread length. Compared to the baseline tests, this increased flame spread led to significantly higher temperatures measured beneath the chipboard in tests with the PV module substitute [39].

These results were compared to larger scale outdoor tests on inclined roof constructions. The outdoor tests were performed with a gap height of 12 cm and various ignition sources. In the test with the most severe ignition source, self-sustained flame spread occurred, and similar to the modified CEN/TS 1187 Test 2, a substantial temperature increase was observed compared to baseline tests without a PV module substitute [39]. As such, Stølen et al. initial work illustrates that CEN/TS 1187 test 2 can be modified so that the flame spread exceeds the acceptance criteria within the cavity below a substitute PV module. However, their work solely examines the influence of a gap height as the single parameter and does not address if the test can be used to differentiate the performance of different roof construction mock-ups installed below a building applied PV system.

Based on the initial work conducted by Stølen et al. [39], the objective of the medium-scale tests is to expand their work slightly and examine if a modified CEN/TS 1187 test 2 can be used to quantify flame spread and heat transfer for two different types of roof constructions discussed in section 4.3.1.

By using the outcome of a single large-scale test as the target for modifying CEN/TS 1187 Test 2, the medium-scale tests will follow a process in which the test setup is gradually adjusted based on the results of previously conducted tests. Therefore, an exact test matrix cannot be defined, but the overall test process can be described. Once the medium-scale setup has been modified to a degree where the outcome resembles that of the initial large-scale test, the tested roof construction can be replaced with a construction featuring a single-ply PVC-based membrane. The outcome of this test can then be compared to the results of the large-scale tests conducted at the end of the experimental campaign.

4.4.1. Adjustments to CEN/TS 1187 and instrumentation

The aim of the test method, based on CEN/TS 1187 Test 2, is to replicate the outcome of the large-scale test or tests when conducted with the same membrane and insulation. Since modifying the dimensions of a PV module causes the tempered glass front sheet to crack [43], an inert surface will be used as a substitute for the PV module, as demonstrated in previous research [22, 25, 26, 39].

A calcium silicate board (CSB) is preferred over a stainless-steel board due to its lower thermal conductivity and ease of replacement. To limit the number of variables, the CSB will be installed parallel to the test surface, consistent with the approach used by Stølen et al. [39].

With an allowable sample depth of 150 mm in CEN/TS 1187 Test 2, the test will be conducted using layers 1, 2, and 3 as specified in Table 1 and illustrated in Figure 3. Additionally, thermocouples will be placed between layers 1 and 3, as well as between layers 2 and 3. As in the work by Stølen et al., the thermocouples will be installed 15 cm apart along the centreline of the 40 cm wide and 100 cm long area of the samples [39].

4.4.2. Test procedure

Gap height, wind speed and the ignition source are considered possible variables in the prioritised order. First, the test method should be adjusted with the aim of achieving a flame spread scenario similar to the binary outcome of the initial large-scale test where self-sustained flame spread is expected based on previously conducted tests on mineral wool [11, 12]. Secondary, the parameters are adjusted to obtain a temperature development in the insulation, similar to the temperatures measure in the large-scale tests. An exact match of the secondary parameter is not expected. However, significantly different temperatures measured in two different large-scale test set-ups, should also yield significant temperature differences in a test method based on CEN/TS 1187 test 2.

- From the tests by Stølen et al., a significant increase of flame spread length was solely observed for the tests conducted with the lowest gap height of 6 cm, which also rendered the largest subjacent temperature increase [39]. Thus, 6 cm is suggested as the initial gap height.
- As the largest temperature increase was measured in Stølen et al.'s modified tests with an applied wind load of 2 m/s, rather than 4 m/s, the initial tests are conducted with the lowest wind load. Previous studies have illustrated that low flame spread rates yields higher subjacent temperatures, due to a slower traveling pyrolysis zone [26], tests will also be conducted with a wind load of 0 m/s. The test method achieving a temperature development closest to the large-scale tests is chosen.
- If self-sustained flame spread is achieved when the tests are conducted with a gap height of 6 cm, additional test are conducted with a gap height similar to lowest gap height of the large-scale test. If self-sustained flame spread is not achieved, an additional layer of five sticks are added to the wood crib from CEN/TS 1187 test 2, which will theoretically increase the HRR [16] and thus, radiative heat flux to the domain of the ignition source [27]. However, the increased gap height outside the domain of the ignition source might yield a lower radiative heat flux towards the pre-heating zone and thus, a slower flame spread rate and higher heat transfer from the burning membrane towards the subjacent insulation.

When the best match is achieved between the modified CEN/TS 1187 test 2 and the large-scale tests with the bitumen-based roofing membrane, the tests are conducted with the PVC-based roofing membrane. The above procedure is expected to require more than 10 tests. However, the above tests are expected to be significantly cheaper than the budgeted cost per test due to i) limited customization of test set-up, and ii) near constant material parameters of the roof built-up.

4.5. Timeline

The three large-scale tests are planned to be conducted on Thursdays in weeks 27, 40 and 42. The medium-scale tests will be conducted in the weeks between week 28 and 39, but exact test dates will depend on availability of the test equipment for CEN/TS 1187 test 2.

4.6. Evaluation of modified test method

When all large- and medium-scale tests are conducted, the potential of a modified CEN/TS 1187 can be evaluated based on the outcome.

a) If significantly different outcomes across the tests of the bitumen-based and PVC-based roof coverings are observed in the developed test method, but not in the large-scale tests, the test method is found inadequate.

b) If no significantly different outcomes across the tests of the bitumen-based and PVC-based roof coverings are observed in the developed test method, but observed in the large-scale tests, the test method is found inadequate.

c) If significantly different outcomes across the tests of the bitumen-based and PVC-based roof coverings are observed in the developed test method and in the large-scale tests, the test method might have potential for further development.

d) If no significantly different outcomes across the tests of the bitumen-based and PVC-based roof coverings are observed in the developed test method, but not in the large-scale tests, the test method might have potential for further development.

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