THE ROOF COMES FIRST · WHITEPAPER

# Beyond flame spread

## What does a separation layer change in a rooftop PV fire?

From surface propagation to direct flame penetration, thermal involvement and total consequence

CENTRAL QUESTION

**How far is a rooftop PV fire allowed to travel into the roof before it becomes a building loss?**

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# Author’s perspective

This series is a synthesis of published research, fire tests, standards, approvals and insurer guidance on fire safety and rooftop PV, written from an explicit roof-first perspective: I look at the complete commercial roof system and the building beneath it rather than at individual product classifications. Within that perspective I summarise what the evidence shows, add my own technical analysis and, where relevant, propose design principles. Those proposals are marked as mine and kept separate from what has been demonstrated.

My background is in architecture and building engineering. Over the past three years I have discussed this subject with engineers, risk specialists, insurers and test institutes, and I have been involved in setting up and supervising fire-test programmes for AllShield's own roof systems. That experience shapes the questions I ask; the papers test those questions against external evidence. How the sources were selected, and what remains open, is described at the end of each paper.

These papers are prepared by Olivier Langejan as lead author with support from a small team. His own professional focus is building and roof design; specialist findings are drawn from the cited evidence, with AI assistance disclosed separately in Method and sources.
I am affiliated with AllShield, which develops BarrierSheet and other roof fire-protection solutions. That commercial relationship is relevant and is therefore stated explicitly. The analysis does not assume that an AllShield product provides the effects discussed. The starting point is the physical or economic problem. Where an AllShield product is discussed, it is treated as one product-specific example and its performance should be read only within the boundaries of the cited tests, approvals and roof assemblies.

In this paper I apply that roof-first approach to one specific question: what changes when a hard separation layer is introduced directly beneath the roof membrane in a rooftop PV fire? I separate three outcomes that are often combined under the term fire spread: surface propagation, direct flame penetration and thermal involvement of deeper layers. This paper was written as part of my role as Chief Commercial Officer of AllShield. AllShield commissioned the product-specific fire-test programmes discussed in Chapter 10, where BarrierSheet is treated as one case study. Chapters 1–9 examine the wider evidence base independently of that product.

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# Executive summary

Fire-safety discussions around rooftop photovoltaic systems often concentrate on ignition and horizontal flame spread. Both are important, but neither fully describes the consequence of a roof fire. Once sustained fire exists beneath a PV array, a second question becomes equally relevant: how far does that fire become involved in the roof construction below? This paper reviews experimental fire research, institutional guidance, material studies and recent roof-PV test programmes from a building-engineering perspective and distinguishes three outcomes that are often combined under the broad term *fire spread*: **surface propagation, direct flame penetration and thermal involvement of deeper layers**. Existing research shows that these three outcomes do not necessarily coincide.

PV changes the thermal environment at the roof surface. Experimental literature reviewed by OFR reports heat fluxes beneath PV arrays of up to approximately 50 kW/m² in some configurations and flame-spread acceleration of up to a factor of 38 below critical cavity heights. The PV module itself can contribute to thermal feedback through flame deflection and reradiation. Roof membrane, wind, module geometry, insulation and particularly the material immediately beneath the membrane can all influence the result.

That material can influence the membrane fire in different ways. A dense board can absorb thermal energy from a thin membrane and act as a heat sink. Highly insulating substrates remove comparatively little heat from the membrane. EPS adds a further mechanism because it can melt and shrink away from the heated zone, changing the thermal boundary condition beneath the roof covering. These effects do not create a simple ranking between combustible and non-combustible insulation. They demonstrate instead that membrane fire and deeper fuel involvement are related but distinct parts of the fire scenario. A separate Kiwa BDA roof-PV programme also showed that broadly comparable surface-fire damage can coexist with markedly different thermal histories deeper in the roof, reinforcing the distinction between visible fire and subsurface thermal involvement.

The distinction between **potential fire load and material actually involved** is central to consequence analysis. Combustible insulation may contain more than 100 MJ/m² of theoretical chemical energy, while only part of that material may actually become involved in a particular incident. At the same time, combustible membrane material remains above any separation layer. A multilayer bituminous waterproofing system can contain combustible energy of the same order as, or greater than, lightweight foam insulation beneath it. A separation layer therefore does not remove fire load from the roof. Its potential function is to alter whether, when and over what area deeper combustible materials become accessible to the fire.

Protective layers can perform this function through different mechanisms. Heavy cement-bonded boards can provide substantial thermal inertia. Mineral-wool layers can interrupt direct access to combustible material while still allowing conductive heat transfer. Gypsum benefits from endothermic dehydration. Thin cementitious layers may operate differently again. Evidence obtained from one material cannot simply be transferred to another because both are called coverboards or both have favourable reaction-to-fire classifications. The relevant unit of evidence is the **complete roof-PV assembly**.

Post-flame behaviour also requires more attention than conventional classifications alone provide. Continuous smouldering is assessed through a dedicated European test method, EN 16733, separately from conventional reaction-to-fire classification. Research on mineral-wool products under prolonged heating shows that organic binders can generate additional heat through smouldering even where the mineral fibres themselves are non-combustible. That research does not concern rooftop PV, but it reinforces a wider point: visible flaming is not the only relevant thermal process after a fire has developed.

The wider consequences remain much less studied than flame spread itself. Smoke toxicity, hidden heating and smouldering, firefighting-water contamination, post-fire repairability and business interruption

are all credible consequence pathways, but few rooftop-PV programmes quantify them. **Fire spread has been tested far more extensively than fire consequence.**

BarrierSheet is examined only after the product-neutral design criteria have been established. ZAG concluded that direct flame penetration into deeper structural layers was prevented in the tested configurations during the documented test periods. Membrane-level propagation, temperatures of approximately 430–800+°C below the sheet, EPS melting and PIR decomposition still occurred, and localised burn-through of the sheet was recorded in two runs. Because no otherwise identical reference roof without BarrierSheet was included, the programme cannot quantify the improvement produced by the sheet. Its comparatively low mass also means that the heat-sink mechanism demonstrated for much heavier cement-bonded boards cannot automatically be attributed to BarrierSheet.

The resulting design principle is intentionally broader than any one product:

> **DESIGN PRINCIPLE**
>
> **For rooftop PV above commercial roof construction, provide an evidenced consequence-limiting strategy that interrupts unnecessary downward fire escalation and verify that strategy for the complete intended roof-PV assembly.**

The question for roof-PV fire safety should therefore not stop at whether ignition occurs or whether fire travels across the roof surface. The more consequential question is **how far that fire is allowed to travel into the roof before it becomes a building loss**. For a designer or risk engineer, that becomes a practical decision: which damage below the PV array is acceptable, and what keeps flames out of the combustible insulation?

## Scope and limitations

This paper focuses on building-applied photovoltaic systems installed above commercial and industrial flat roofs. Building-integrated PV, façade systems and pitched residential roofs are included only where their evidence helps explain a mechanism relevant to flat-roof design. The typical layer sequence considered is **PV module → air cavity → roof membrane → optional separation layer → insulation → structural deck**.

The paper is a review and engineering synthesis. It does not present new fire testing, numerical modelling or toxicological experiments. Evidence is described on the two axes used throughout the series and defined in What does a fire test actually prove?. For the claim, **DEMONSTRATED** means that an outcome or mechanism was directly observed or measured in a relevant test. **PHYSICALLY SUPPORTED** means that a mechanism is supported by established physical behaviour or related evidence, but has not been demonstrated for the relevant roof-PV assembly. **CONTRADICTED** means that relevant evidence is incompatible with the claim. **UNKNOWN** means that the evidence does not establish the answer either way. For the route to the intended roof, a result can be as tested, formally covered by a classification, field of application or approval, or engineering extrapolated. The two axes are kept separate: formal coverage does not demonstrate behaviour beyond the tested question, and strong physical evidence does not create formal coverage.

Results are treated as assembly-specific unless the underlying evidence supports wider applicability. A result obtained with one membrane, insulation, coverboard, fixing method or PV geometry is not automatically transferred to another. Industry-commissioned research is included where technically relevant, but commissioning or financial support is identified where known.

# 1. Why flame spread is only part of the question

## PV creates a different roof-fire exposure

The presence of PV can substantially alter the fire exposure experienced by a commercial flat roof. The cavity beneath modules can redirect flames, increase radiative feedback and retain heat close to the waterproof membrane. A literature review prepared by OFR Consultants for the UK Building Safety Regulator reports experimental heat fluxes beneath PV arrays of up to approximately 50 kW/m² in some configurations, compared with 12.5 kW/m² in the conventional roof-fire exposure discussed in that review. [1] The importance of this comparison is not that every PV fire produces 50 kW/m², but that adding PV can create a materially different fire environment from the exposure represented by conventional roof testing.

Ignition prevention remains essential. Connector compatibility, cable routing, electrical design, installation quality, inspection, maintenance and fault detection all reduce the probability that an electrical defect develops into sustained fire. FM treats these measures as part of the wider roof-PV risk picture. [2] Once sustained fire exists, however, the engineering question changes. The important issue becomes how the fire interacts with the roof beneath it and whether the roof contains a meaningful stopping point before that fire can involve deeper construction.

## Three outcomes that should not be confused

This paper therefore distinguishes three outcomes. **Surface propagation** describes fire travelling at membrane level beneath or around the PV field. **Direct flame penetration** describes flame or burning material physically crossing into deeper roof layers. **Thermal involvement** describes underlying material becoming hot enough to soften, melt, shrink, decompose, char or smoulder even where direct flame penetration does not occur.

These outcomes are related but they are not equivalent. Kristensen and Jomaas showed in multi-module PV experiments that extensive membrane-level fire could coexist with delayed involvement of the EPS beneath protective layers. [3] Kristensen’s later doctoral work reinforces the same distinction between fire above a protective layer and thermal damage below it. [4] This means that a fire test cannot be understood from flame footprint alone. A roof may look severe at the surface while deeper involvement remains limited, or it may suffer substantial subsurface damage beneath a relatively localised fire.

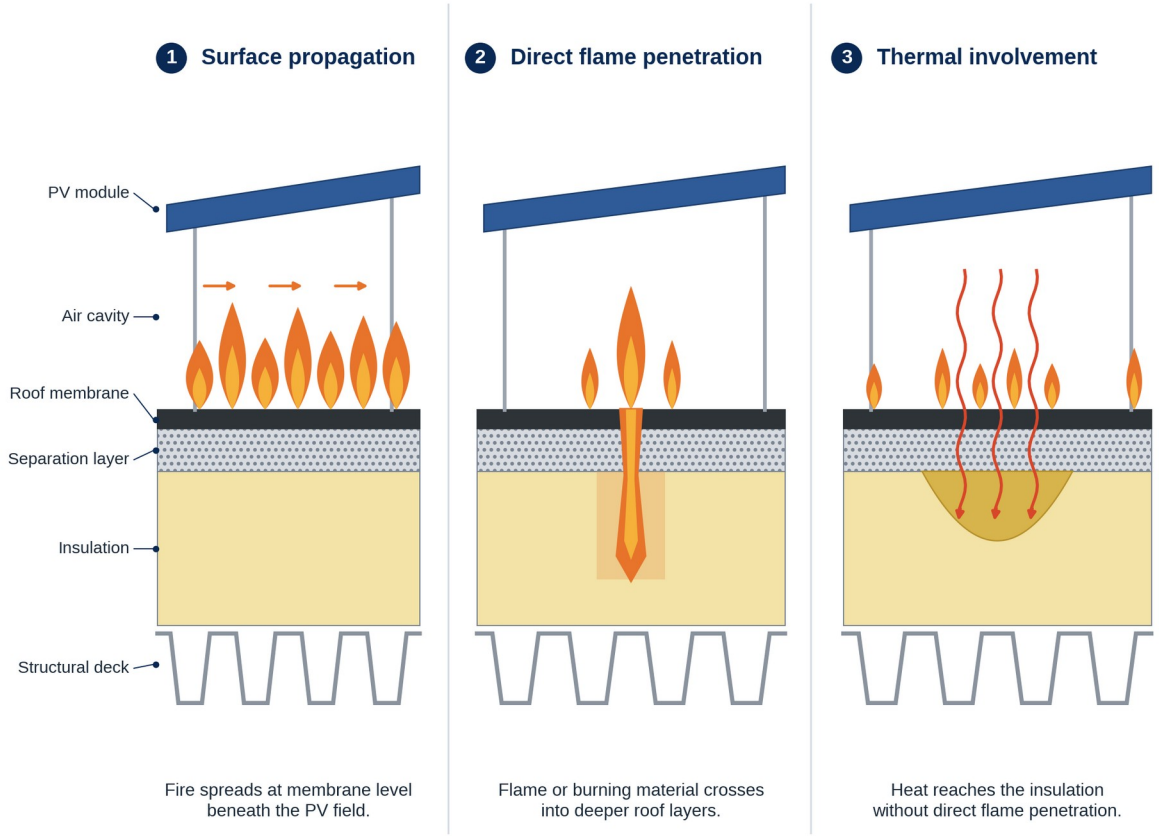



*Figure 1. Surface propagation, direct flame penetration and thermal involvement are different outcomes in a rooftop PV fire.*

These three outcomes correspond to three distinct protection objectives: limiting surface propagation, limiting direct flame penetration and limiting thermal damage below a protective layer. Two further objectives lie on either side of this paper. Preventing ignition is primarily an electrical, installation and maintenance question, addressed in the series' two papers on DC arcs. Preventing a roof fire from becoming a building-scale loss is the ultimate outcome; it depends on more than the roof build-up alone and is discussed in Chapter 8. A measure can perform well against one of these objectives and have limited effect on another.

## Incident data show a wider operational problem

Real incidents add another perspective. NIPV research into Dutch building fires involving PV found that practical intervention can continue after visible extinguishment because electrical safe-making, panel removal or other measures may still be required. [5] Earlier British work reviewed 58 fires involving PV systems, while TÜV Rheinland and Fraunhofer ISE analysed approximately 210 PV-related fire incidents in Germany. [6,7] These datasets focus strongly on ignition, electrical design, installation and emergency response and therefore complement rather than replace controlled experimental research.

The consequence chain also does not stop at the insulation. FM documents that combustible roof materials such as XPS can melt, burn and flow and that roof fires can damage steel decking or enable fire and smoke to affect the building interior. [2] Consequence limitation should therefore not be defined only as limiting visible flame travel across the roof. Its broader purpose is to reduce progressive involvement of deeper layers and the opportunity for a roof-level incident to become a building fire.

## Removing combustible insulation is one route, not the whole answer

Removing combustible insulation is one direct way to reduce that pathway. The ZAG/FRISSBE *Fire Safety Guideline for Building Applied Photovoltaic Systems on Flat Roofs* (2024) identifies non-combustible insulation as its primary recommendation where practical. The work acknowledges economic support from ROCKWOOL and funding through the EU Horizon 2020 FRISSBE project. [8]

At the same time, more recent roof testing has shown that membrane-level fire can still propagate above non-combustible insulation. In the EUMEPS/IVH programme analysed by DBI, a mineral-wool reference construction still developed significant membrane-level fire. [9] Non-combustible insulation removes a major fuel source from the deeper roof construction, but it does not make the membrane or PV cavity inert.

> **KEY QUESTION**
>
> **The key question is therefore not simply whether the insulation itself is combustible. It is how much of the roof construction actually becomes involved once a rooftop PV fire has started and what determines that involvement.**

# 2. How roof insulation materials behave in fire

## Different materials fail differently

Roof insulation materials do not respond to fire through one common mechanism. Thermoplastic foams can soften, shrink and melt. Thermoset foams decompose and char. Mineral-fibre insulation can remain largely intact while binders, facings and adjacent materials degrade. These distinctions are more useful than a simple combustible-versus-non-combustible division when considering what a protective layer above the insulation can actually influence.

PIR is a thermoset foam. Under continued heating its polymer structure decomposes, char develops and gaseous degradation products are released. There is no single universal PIR failure temperature. McKenna and Hull describe decomposition of different polyurethane and polyisocyanurate chemical structures across a broad temperature range, with some urea and urethane structures degrading from approximately 160–200°C and more thermally stable carbodiimide and isocyanurate structures persisting to higher temperatures. [10] These are chemical-bond decomposition ranges rather than universal roof-board failure temperatures.

Hidalgo, Torero and Welch reported peak heat-release rates of approximately 120–170 kW/m² for the PIR material they examined and an effective heat of combustion around 13–16 MJ/kg. [11] These values are test-specific, but they illustrate that heat released during an actual fire exposure can differ substantially from a material's gross calorific potential. Facings can alter the mechanism further. De Paula, Rodrigues and Camargo observed expansion of aluminium-faced PIR followed by rupture of the facing and release of degradation gases. [12]

## Thermoplastic insulation can fail before sustained ignition

EPS behaves differently. As a thermoplastic foam it can soften, shrink and melt before sustained flaming ignition occurs. This means that ignition is not the only meaningful failure criterion. Melted or shrunken EPS has already lost geometry and mechanical support even where sustained flaming combustion has not occurred. The quantitative Kristensen roof-PV results, including the measured temperatures, piloted-ignition range and time to penetration of the PIR mitigation layer, are discussed in Chapter 4 rather than repeated here. [3]

The term *flame-retarded EPS* also requires historical context. It should not automatically be read as one fixed chemical formulation. Legacy European EPS and XPS insulation can contain the brominated flame retardant HBCDD, which is now regulated as a persistent organic pollutant. This is particularly relevant to renovation and demolition because an existing roof can contain insulation chemistry that differs from a newly manufactured test specimen. [13] The Kristensen paper identifies its EPS as flame-retarded, but that description alone should not be used to infer which particular flame-retardant chemistry was present.

XPS is likewise thermoplastic. FM describes combustible XPS roof insulation as capable of melting, burning and flowing and cites property-loss scenarios in which involvement damaged steel roof decking. [2] The detailed thermal behaviour of EPS and XPS differs by density, formulation and facing, but both demonstrate why preservation of geometry can matter even before complete fuel involvement occurs.

## Thermoset foams char rather than melt away

PUR, PIR and phenolic foam should not be treated as variants of EPS. Their thermoset structure prevents the same type of melt-flow behaviour. Instead, continued heating produces decomposition,

gaseous products and a residual char layer. The stability and protective value of that char differ between products and exposure conditions.

The char itself does not guarantee that deeper material remains unaffected. Hidalgo, Torero and Welch observed oxidative smouldering processes within the char of PIR and phenolic foam. [11] Crewe and colleagues likewise showed in larger sandwich-panel experiments that pyrolysis products from PIR can escape at joints, ignite and materially increase the fire exposure of the surrounding construction. [14] Those wall and enclosure tests are not rooftop-PV tests, but they demonstrate why material that appears physically present can nevertheless be actively participating in the fire.

## Non-combustible insulation does not make the roof system inert

Stone wool provides relatively little combustible fuel compared with polymeric foam. The mineral fibres themselves are non-combustible, although commercial boards can contain organic binders, facings and adhesives. De Paula and colleagues observed smouldering associated with binder material near joints during roof-covering experiments. [12] The result is relevant because it shows that hidden thermal activity is not limited to combustible foam insulation.

Continuous smouldering is a separate fire characteristic from conventional A1–F and smoke/droplet reaction-to-fire classification. EN 16733:2016 provides a dedicated method for determining a building product's propensity to undergo continuous smouldering following exposure to an open flame under natural convective airflow. [15,16] The test is intended for building products classified according to EN 13501-1, while mounting conditions and the field of application are defined through relevant product standards or technical specifications.

Leppänen and Malaska investigated A1-classified mineral-wool products used in chimney penetrations under sustained heating. Their experiments showed that smouldering of organic binder can generate additional heat and that the resulting temperature rise was related to the amount of organic material per unit volume. [17] They also identified an important limitation of EN 16733 for prolonged heating scenarios: the standardised open-flame exposure does not reproduce continuous thermal loading. Their experiments concerned chimney penetrations rather than roofs and should not be transferred directly to a roof-PV assembly.

The distinction matters because the mineral fibres can remain non-combustible while organic constituents still participate in post-flame thermal activity. This should not be interpreted as evidence that mineral wool is comparable with combustible foam insulation. It remains a direct route to removing a substantial combustible fuel source from the deeper roof construction. The relevant point is narrower: **non-combustible fibres do not mean that every component of every mineral-wool product is thermally inert under prolonged exposure**.

More importantly, non-combustible insulation beneath a membrane does not automatically prevent membrane fire. The EUMEPS/IVH programme included a mineral-wool reference configuration in which substantial membrane-level propagation still developed. [9] The insulation can therefore reduce combustible involvement in depth without removing the exposed membrane fire above it.

Glass wool belongs to the same broad mineral-fibre family but should not be assumed to behave identically to stone wool at high temperature. Product density, fibre composition, binder and facing all matter.

## Fire effluent comparisons need a common basis

Stec and Hull found substantial differences in the toxicity of combustion products from different insulation materials under their laboratory conditions. The mineral-wool products generated a relatively small toxic

contribution, while organic foams produced larger quantities of combustion products including CO and, for nitrogen-containing foams such as PIR and PUR, HCN. [18] McKenna and colleagues likewise reported substantially higher toxic smoke production from some organic façade insulation systems than from mineral wool. [19]

Those comparisons require an important qualification. Stec and Hull compared test specimens on a **mass basis**. They did not compare complete roof constructions per square metre and they did not normalise the materials to equal thermal resistance. A lightweight PIR roof and a much heavier mineral-wool roof can therefore contain very different insulation masses per square metre even when they provide the same thermal function. The toxicology results are valuable for understanding material chemistry, but they should not be converted directly into a roof-level toxicity ranking.

## An overview of the main insulation families

*Table 1. Fire response of the main roof insulation families.*

| Insulation family | Typical response to severe heating | Combustion / degradation relevance | What a layer above it may need to influence |
|---|---|---|---|
| **Stone wool** | Fibres remain non-combustible; organic binders or facings can degrade and, depending on product and exposure, may support smouldering | Low combustible contribution compared with organic foams | Membrane behaviour, heat transfer, joints and mechanical continuity |
| **Glass wool** | Inorganic fibres provide little combustible contribution; binders and facings remain product-dependent | Low combustible contribution | Heat transfer and preservation of the roof system |
| **EPS** | Shrinks and melts before or during ignition and can lose support geometry | Combustible thermoplastic; smoke and CO when involved | Delay heating, retain separation and restrict direct flame access |
| **XPS** | Thermoplastic and capable of melting, burning and flowing | Combustible and capable of molten involvement | As for EPS, with attention to melt-flow pathways |
| **PIR** | Decomposes and chars rather than melting away | CO, HCN and combustible pyrolysis products can be produced | Delay decomposition and interrupt flame or gas pathways |
| **PUR** | Decomposes under heating and is generally less thermally stable than PIR | CO, HCN and combustible degradation products | Delay decomposition and direct fire involvement |
| **Phenolic foam** | Forms substantial char | Combustible decomposition and smoke remain relevant | Maintain separation and delay penetration |
| **Cellular glass** | Inorganic closed-cell glass and non-combustible | Little combustible fuel contribution | Can combine insulation and physical-separation functions |

The table is intentionally descriptive rather than ordinal. No single row determines total roof fire performance because membrane, substrate, PV geometry, attachment and exposure remain part of the system.

## Failure criteria should remain material-specific

A single universal temperature criterion cannot describe all insulation families. EPS can cease to perform its intended function by melting. PIR can remain physically present while decomposing internally. Mineral wool can retain its fibres while binders, facings or neighbouring layers have deteriorated. Hidalgo, Welch and Torero consequently argue for material-specific performance criteria rather than one universal threshold. [20]

For many building products classified A2 to D, EN 13501-1 uses results from the Single Burning Item test (EN 13823), including the fire growth rate index (FIGRA), total heat release during the first 600 seconds

(THR600s) and lateral flame spread, alongside other class-specific criteria. These parameters describe a product’s early reaction to fire under a defined exposure. They do not describe fire behaviour in the semi-enclosed cavity beneath PV, the depth of thermal involvement within a roof assembly or prolonged post-flame behaviour. [15,21]

The same principle applies to smouldering. A conventional reaction-to-fire classification, a continuous-smouldering assessment and system behaviour under prolonged roof-PV heating answer different questions.

# 3. The roof membrane is part of the fire system

## PV changes the membrane exposure

The waterproof membrane is located directly beneath the PV cavity and receives convective and radiative heat from the fire above. Kristensen, Jacobs and Jomaas showed experimentally that the semi-enclosed cavity beneath a PV module can create threshold behaviour. Below critical gap heights in their tested configurations, reradiation and flame confinement were sufficient to support self-sustained propagation. [22] The exact critical height is configuration-specific, but the broader mechanism is important: adding PV changes the fire exposure experienced by the membrane.

The same system dependence appears throughout the OFR review. Gap height, panel inclination, module dimensions, array arrangement, roof material and wind can all influence fire development. [1] A membrane classification obtained without PV should therefore not be read as a complete prediction of its behaviour once modules are positioned above it.

## Membrane chemistry and attachment influence propagation

De Paula, Rodrigues and Camargo conducted an extensive CEN/TS 1187 Test 1 experimental campaign using PVC and TPO membranes over PIR and stone wool under different inclination and wind conditions. There were no PV modules in those experiments. Within their test matrix, membrane type and wind had stronger effects on propagation than insulation type, although insulation still had a measurable influence. [12]

Attachment provides another pathway. Ödeen's earlier experimental roof-fire work showed that fire behaviour can differ between fully bonded coverings and those with partial or point-wise attachment because hot gases or flames can develop beneath portions of the roof covering. [23] The work predates modern rooftop PV, but the mechanism remains relevant wherever a membrane can lift, shrink or create a concealed pathway.

PVC also illustrates why the membrane itself should not be treated as inert. Thermal degradation includes dehydrochlorination and release of HCl. [12] A separation layer underneath the membrane cannot remove smoke or corrosive degradation products generated by material that remains above that layer.

## Wind is not a secondary detail

Wind affects both flame inclination and the supply of oxygen to the cavity beneath PV. The de Paula programme found wind to be one of the dominant variables in roof-covering propagation. [12] In the EUMEPS/IVH programme, DBI also associated the one cement-board configuration that continued to propagate after removal of the burner with higher wind exposure. [9]

This means that a roof-PV assembly cannot be assessed solely from its vertical section. The same membrane and insulation sequence can experience a different thermal challenge depending on wind direction, module arrangement and the open edges of the array.

## The layer beneath the membrane can influence the fire above it

The interaction also works downward-to-upward. The material immediately beneath a thin membrane can influence its temperature and fire behaviour. The EUMEPS/IVH programme is particularly informative here. DBI concluded that the thermophysical properties of the substrate beneath the PVC membrane

materially influenced whether self-sustained propagation continued after the external burner was removed. [9]

In several configurations, a 12 mm cement-bonded particle board provided sufficient thermal inertia for the fire to die after burner removal. That observation is specific to a relatively heavy board and should not be extrapolated to thinner products. In the bituminous configuration, fire still propagated beneath the PV field even with the board present, while EPS damage below the board remained much more localised. Surface propagation and depth of involvement therefore diverged within the same construction.

## The substrate can change the thermal boundary condition

The material immediately beneath a thin waterproofing membrane can influence the membrane fire without itself becoming a major fuel source. Earlier comparative roof-covering tests by the Swedish National Testing and Research Institute showed that **substrate thermal inertia** can materially affect flame spread. A substrate with low thermal inertia removes relatively little heat from the roof covering, leaving more thermal energy near the exposed membrane. [24]

EPS introduces an additional mechanism because the substrate can change during the fire. In the SP tests, EPS melted away from the heated zone and created a void beneath the roof covering. The authors concluded that this reduced the insulating effect beneath the membrane or induced cooling air movement. Where the fire did not penetrate the roof covering and ignite the EPS, damage to the roof covering on EPS was approximately 20% shorter on average than over mineral wool and in some cases up to 50% shorter. [24]

The reverse outcome is equally important. Once the EPS itself ignited, the fire behaviour became substantially more severe and the complete test specimen could become involved. [24] The SP work concerned the selection of a standard substrate for conventional roof-fire testing under ENV 1187 test method 2 and contained no PV modules. It should therefore be treated as evidence for a **substrate mechanism**, not as direct evidence that an EPS roof performs better than a mineral-wool roof beneath PV.

A dense coverboard can create a different thermal boundary condition. In the EUMEPS/IVH programme analysed by DBI, a 12 mm cement-bonded particle board beneath a thin PVC membrane was interpreted as a heat sink. [9] The important mechanism is not that the board prevents heat from being generated. A sufficiently thermally massive layer can absorb energy from the membrane and alter whether membrane-level combustion remains self-sustaining. This mechanism cannot be transferred automatically to thinner or materially different boards.

PIR introduces another nuance. In PV-related experimental work by Kristensen and colleagues, temperatures measured within aluminium-faced PIR were lower at depth than within the mineral-wool protection used for comparison. [22] The authors attributed part of that difference to the low absorptivity of the aluminium facing, which can reduce radiative transfer into the board. This should not be interpreted as a permanent property of an intact reflective surface under all fire conditions. De Paula and colleagues observed expansion and rupture of aluminium facing on PIR during severe heating, demonstrating that the facing itself can change during the event. [12]

The PV module itself provides another distinct thermal feedback mechanism. Kristensen, Merci and Jomaas investigated fire-induced reradiation beneath photovoltaic arrays and showed that an inclined PV module can increase heat flux to the surface below through flame deflection and reradiation from the heated panel. [25] The system therefore contains several different mechanisms that should not be conflated:

- the PV module can reradiate heat towards the roof;

- aluminium facings can temporarily reduce radiative absorption;
- insulation controls conductive heat transfer;
- a dense board can absorb energy through thermal inertia;
- EPS can physically retreat from the heated area;
- thermoset insulation can decompose and char while remaining in place.

The relevant distinction is therefore not simply combustible versus non-combustible insulation. A non-combustible insulation can remove combustible fuel from the deeper roof construction while still providing a thermal boundary that affects the membrane fire above it. Conversely, a combustible substrate such as EPS may temporarily reduce membrane-level propagation by melting away, but that apparent benefit disappears if the EPS itself becomes involved in sustained flaming combustion.

A separate Kiwa BDA comparison of mineral-wool and PIR roof-PV assemblies further illustrates that similar membrane-level fire behaviour can coexist with substantially different temperature development deeper in the roof. [26] The programme is discussed in Chapter 4 and its post-fire implications in Chapter 8.

## Existing roof classifications have limits once PV is added

This system interaction has a direct implication for conventional roof classifications. FM Data Sheet 1-15 states explicitly that, unless a combination is specifically FM Approved as a roof-PV system, placing PV panels above an FM Approved Class 1A roof assembly negates that Class 1A rating for the combined configuration. [2]

The same caution applies more broadly to external-roof-fire classifications. BROOF(t1), for example, describes performance under a specified CEN/TS 1187 Test 1 exposure and within a defined field of application. It does not reproduce every PV cavity, wind condition or prolonged heat exposure identified in the research reviewed here.

The four CEN/TS 1187 methods address different external-fire scenarios, with no generally acceptable EU-level hierarchy between them; national hierarchies may apply. This does not make t1–t4 equivalent. The Efectis BROOF(t1) evidence concerns the specified two-BarrierSheet PVC/PIR construction and its permitted variations, rather than a generic single-layer, TPO or bituminous configuration. The methods and national routes are explained in What does a fire test actually prove?, Chapter 8.

## Operational roofs are not new test specimens

Laboratory fire tests normally use new materials. Operational roofs do not. Ivanič and Lubej documented shrinkage, wrinkling, cracking and mechanical changes in PVC-P roofing after long-term service. [27] Pedrosa and Del Río likewise reported chemical and physical deterioration in ageing PVC-P waterproofing membranes, including changes that were not always obvious through visual inspection. [28]

Neither study is a rooftop-PV fire test. Their relevance is narrower but important: a roof presented to a fire after ten or fifteen years may not behave exactly like the new membrane used in a laboratory classification.

# 4. What existing rooftop PV fire tests actually show

## PV changes the test exposure

The experimental evidence has developed in stages. Early programmes demonstrated that a roof classification and a PV-module classification cannot simply be treated as independent fire-safety questions. Later studies investigated the cavity beneath the modules and the role of roof materials. More recent programmes have introduced multiple modules, wind, alternative PV geometries and protection layers. The combined evidence is now strong enough to identify recurring mechanisms, but still too heterogeneous to justify a simple ranking of roof constructions.

The UL/Solar ABCs programme provided an early system-level warning. Tests combined stand-off PV modules with roof coverings that already held recognised fire classifications and found cases in which the roof no longer achieved the same spread-of-flame performance once PV was installed above it. [29]

Later research explained why. The OFR review reports experimental heat fluxes beneath PV arrays of up to approximately **50 kW/m²** in some configurations and flame-spread acceleration of up to a factor of **38** below critical cavity heights compared with corresponding conditions without PV. [1] The factor 38 is not a universal PV multiplier. It is an extreme result from particular experimental conditions.

Kristensen's doctoral work and the related experiments with Jacobs and Jomaas show how the semi-enclosed PV cavity can create threshold behaviour. [4,22] Wang, Wang and Zhao examined roof material, inclination, wind and module spacing across thirteen full-scale experiments and again found strong interaction between geometry, environment and roof construction. [30]

## Protection above heat-sensitive insulation

Kristensen and Jomaas provide some of the clearest evidence of the difference between surface fire and involvement in depth. Their 2018 programme used four roof mock-ups with six PV modules above EPS/PVC roofs. The mitigation consisted of either **40 mm PIR** or **30 mm mineral wool** above the EPS. The work was partly sponsored by IKEA Services AB. [3]

In all four experiments the fire propagated beneath the entire six-module field but did not continue as self-sustained propagation beyond the array. Before penetration of the PIR layer, the maximum measured temperature below it was approximately **175°C**. Beneath the mineral wool the maximum was approximately **243°C**. Both values were more than 100°C below the cited **366–405°C piloted ignition range** for the flame-retarded EPS used in the tests. [3]

That did not make the protection indefinite. In the PIR-protected configuration, progressive thermal degradation eventually produced penetration after approximately **63 minutes**. Once that occurred, temperatures within the EPS increased sharply and the EPS became involved. In the mineral-wool test the peak below the protection occurred earlier, around 34 minutes, after which temperature decreased as combustible material above was depleted. [3]

The programme therefore demonstrates a central principle of this paper: a protective layer can materially change the timing and depth of involvement without necessarily stopping the surface fire above it.

A 2024 ZAG programme comparing vertical and inclined PV arrangements provides another perspective. Public reporting describes limited EPS damage where a mineral-wool protective layer was used and identifies module geometry as an important influence. The commissioning and funding relationship has not been established from the public sources reviewed for this paper, so no sponsorship inference is made. [31]

The EUMEPS/IVH programme performed by Kiwa BDA at Twente Safety Campus adds a larger-roof comparison. Seven approximately 7 × 7 m roof tests used east-west PV arrays and a nominal 15 kW burner for 10 minutes. The programme was commissioned by EUMEPS and IVH and later analysed by DBI. The complete Kiwa reports were not publicly available during preparation of this paper, so detailed interpretation relies partly on secondary reporting of DBI's analysis. [9]

In the PVC/EPS baseline without the cement-bonded board, fire travelled beneath the PV field. The EPS initially became involved, then melted away from the flame and self-extinguished. Four later configurations used a 12 mm cement-bonded particle board. In three of those configurations self-sustaining propagation reportedly ceased after the burner was removed, with DBI interpreting the board principally as a heat sink. [9]

The mineral-wool reference did not contain the cement-bonded board. Membrane fire developed and the test was stopped after approximately 11 minutes once propagation had become established. In the bituminous configuration, fire propagated beneath the PV array while EPS damage below the board remained substantially more localised. [9]

A separate Kiwa BDA programme commissioned by PU Europe compared two 6 × 6 m roof-PV assemblies using the same 1.5 mm PVC membrane and east-west PV arrangement but different insulation systems: 260 mm mineral wool and 142 mm PIR. The specimens were constructed by members of PU Europe under supervision by Troned. Kiwa BDA conducted the fire tests and measured surface fire spread, while the temperature measurements were performed by Troned and supplied to Kiwa afterwards. The fire was deliberately not extinguished, in consultation with the principal, to observe the behaviour during and after the PV panels had burnt down. The document reviewed here is an additional report to report 0151-L-21/3, with product brand names removed at the principal's request. [26]

Kiwa described the total burnt roof-covering area as broadly comparable, while noting that changing wind direction strongly influenced flame spread. The most important difference was the thermal history within the roof; those post-fire temperatures are discussed in Chapter 8. The programme contained one test of each construction and should not be interpreted as a generic ranking of PIR and mineral wool.

## Different tests identify different governing variables

The studies do not always identify the same dominant variable. The ZAG/FRISSBE guideline places strong emphasis on insulation combustibility and recommends non-combustible insulation as the primary consequence-limiting route where practical. [8] De Paula and colleagues, by contrast, found membrane type and wind to be more influential than insulation within their CEN/TS 1187 roof-covering experiments without PV. [12]

The results are not necessarily contradictory because the exposure is different. De Paula isolates roof-covering behaviour under a prescribed external-fire test without the PV cavity. ZAG/FRISSBE synthesises evidence from the modified environment created beneath PV. The SP work adds a third perspective by showing that the thermal boundary immediately beneath the membrane can itself alter conventional roof-covering fire behaviour. [24]

## Ignition source, duration, wind and scale remain part of the result

Wood cribs and gas burners provide controlled thermal challenges but do not physically reproduce a DC arc fault, a burning connector or every internal building fire. Their value lies in repeatability. Their limitation is that fire behaviour observed under one source intensity or duration cannot automatically be extended to a much longer or more severe event.

Wind creates another boundary because it influences flame orientation, ventilation and convective transfer beneath modules. De Paula demonstrated the significance of wind directly, while the EUMEPS interpretation also identified differing wind exposure as a likely contributor to one divergent board result. [9,12]

Southwest Research Institute has undertaken large commercial-roof-scale testing supported by the NFPA Fire Protection Research Foundation and the Property Insurance Research Group. [32] Detailed final public data remain limited, so that programme is treated here as emerging evidence rather than a basis for numerical design claims.

## Evidence overview

*Table 2. Overview of rooftop-PV fire test programmes reviewed.*

| Programme | Configuration / contribution | Commissioning or funding context | Important boundary |
|---|---|---|---|
| **UL / Solar ABCs [29]** | Stand-off PV above classified roofs; established need for system assessment | Solar ABCs / UL research | US classification framework |
| **Kristensen & Jomaas [3]** | Six-module PV tests over EPS/PVC with PIR or mineral-wool protection | Partly sponsored by IKEA Services AB | Four specific configurations; no unprotected reference |
| **Kristensen et al. [4,22,25]** | Cavity geometry, reradiation and critical gap-height research | Academic research | Geometry-specific |
| **ZAG vertical PV [31]** | Vertical versus inclined PV and protective-layer behaviour | Commissioning/funding not established from reviewed sources | Publicly reported programme |
| **ZAG / FRISSBE [8]** | System-level BAPV guidance | ROCKWOOL support and Horizon 2020 / FRISSBE | Guideline synthesis |
| **EUMEPS / IVH [9]** | Seven ~7 × 7 m roof-PV tests | Commissioned by EUMEPS and IVH | Variables change between tests; full Kiwa reports not public |
| **Kiwa / PU Europe [26]** | Two 6 × 6 m PVC/PV roofs comparing 260 mm mineral wool and 142 mm PIR; strongly different subsurface thermal histories | Commissioned by PU Europe; specimens built by PU Europe members; temperature measurements by Troned | One test per construction; wind direction differed; no separation layer; fire deliberately not extinguished |
| **Wang et al. [30]** | Thirteen full-scale tests | Publicly funded research | Different constructions from many European commercial roofs |
| **SwRI / NFPA FPRF [32]** | Large-scale roof-PV mitigation research | NFPA FPRF and Property Insurance Research Group | Detailed public dataset incomplete |

Taken together, the evidence supports a more precise interpretation than the binary question of whether a roof burns. PV geometry can increase exposure, membrane-level propagation can occur over combustible and non-combustible insulation and intermediate layers can delay or limit deeper involvement even while fire continues above them.

# 5. From theoretical fire load to material actually involved

## Potential fire load is not the same as fire consequence

A combustible insulation material introduces chemical energy into the roof. In simplified form:

**potential fuel contribution = combustible mass present × gross heat of combustion**

This is useful because it converts thickness, density and calorific value into one roof-area-based quantity, but it does not describe how much heat a particular fire will actually release.

PIR illustrates the distinction. Lakatos, Csontos and Csík measured gross heats of combustion around 27 MJ/kg for the PIR products they examined. [33] Hidalgo, Torero and Welch reported an effective heat of combustion around 13–16 MJ/kg for PIR under their experimental fire conditions. [11]

A directly comparable effective value has not been identified for the representative roofing EPS used in the illustrative calculation below. That asymmetry should remain explicit rather than being filled with a value from a different EPS product.

## Comparing insulation at the same thermal function

A meaningful roof comparison should also normalise thermal performance. The following example uses an insulation resistance corresponding to approximately **Rc 6.3 m²K/W** as a common reference. Strictly, Rc describes the thermal resistance of the complete construction. Here the value is applied to the insulation alone as a simplified normalisation.

*Table 3. Illustrative insulation mass and potential combustible energy at equal thermal resistance.*

| Insulation | λ used | Approx. thickness | Approx. mass | Calorific basis | Indicative potential energy |
|---|---|---|---|---|---|
| **EPS** | 0.035 W/mK | 221 mm | 4.4 kg/m² | 39.6 MJ/kg gross | ≈175 MJ/m² |
| **PIR** | 0.022 W/mK | 139 mm | 4.2 kg/m² | ≈27 MJ/kg gross | ≈112 MJ/m² |
| **PIR, same mass** | : | : | 4.2 kg/m² | 13–16 MJ/kg effective | ≈54–67 MJ/m² under comparable involvement |
| **Stone wool** | 0.038 W/mK | 239 mm | ≈28.7 kg/m² | A1 classification basis | Limited combustible contribution |
| **Cellular glass** | 0.036 W/mK | 227 mm | ≈21.5 kg/m² | A1 | Not treated as equivalent combustible fuel |

Representative product values are drawn from current PIR, mineral-wool and cellular-glass data. [34–36] Stone wool should not be treated as literally zero calorific content. Commercial products can contain binders. For homogeneous A1 products an EN ISO 1716 gross heat-of-combustion criterion forms part of the classification framework. [37]

The structural and fire trade-off is therefore clear. Polymer foams achieve high thermal resistance with comparatively little mass while still representing substantial potential combustible energy. Mineral products require much greater mass for the same thermal function but add much less combustible fuel.

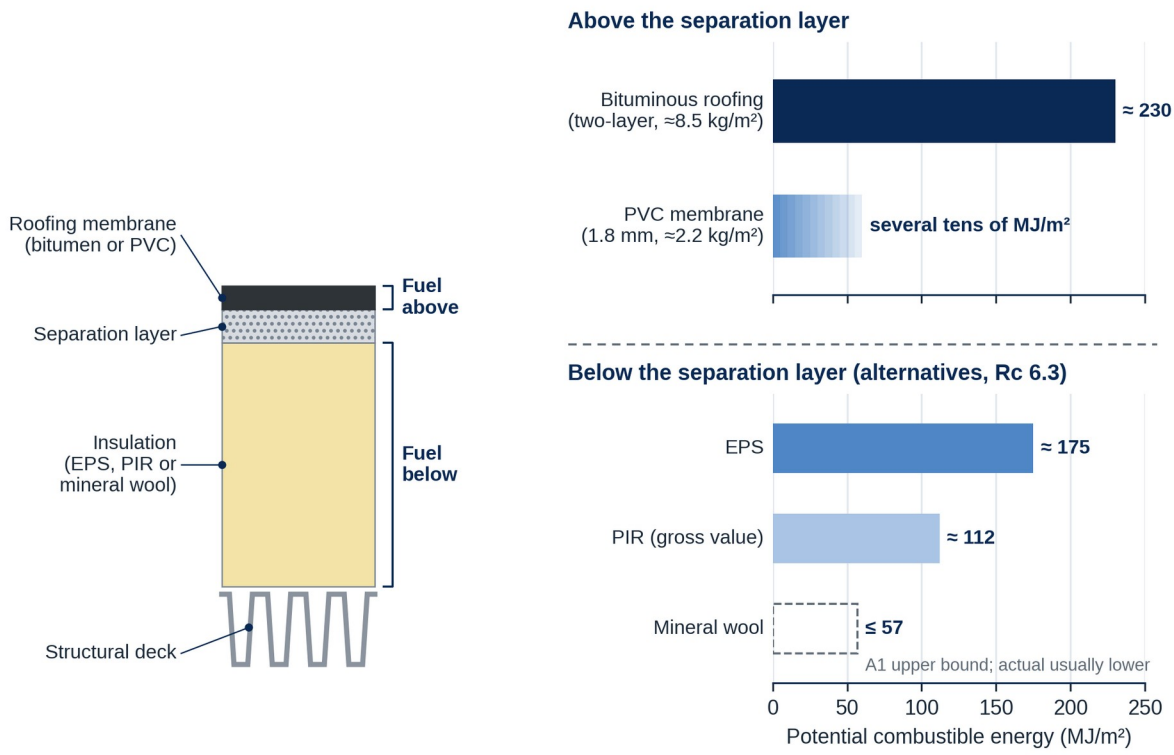
## Fuel also exists above the separation layer

An insulation-only calculation still misses a major part of the roof. A protective layer installed beneath the waterproof membrane leaves the membrane entirely on the exposed side. A representative PVC-P

roofing membrane represents **several tens of megajoules per square metre** of potential combustible energy depending on membrane mass and formulation. [38]

Bituminous systems can contain substantially more mass. The BMI Icopal 500 EPD describes a fully torched two-layer waterproofing system with a declared installed mass of approximately **8.5 kg/m²**. [39] Using an illustrative complete-roofing fire-load value around 27 MJ/kg from the NEN 6090 framework gives approximately **230 MJ/m²**. [40]

The significance is the order of magnitude rather than the precise number. A bituminous roof can contain as much or more potential combustible energy **above** a separation layer as lightweight foam insulation contains below it.




Illustrative values for representative constructions. A separation layer does not remove the fuel above it; it can change access to the fuel below it.

*Figure 2. Illustrative potential fire load above and below the separation layer. Values represent example constructions, not universal material properties, and do not indicate how much fuel actually becomes involved in a PV fire.*

## From available fuel to involved fuel

A second expression is therefore more useful for consequence analysis:

**realised fire contribution ≈ mass actually involved × effective heat of combustion**

This is not proposed as a predictive engineering model but as a conceptual distinction. A protective layer does not remove the chemical energy contained in retained combustible insulation. It can influence whether that material is reached, how quickly it heats, how deeply it decomposes and over what area it becomes involved.

The term **accessible fire load** is useful as a conceptual description, but it is not yet a standardised fire metric. Future research would benefit from consistent measurement of **affected area, affected depth and involved mass**.

# 6. What can a hard separation layer actually change?

## Outcome and mechanism are not the same

A hard layer beneath a roof membrane is often described simply as a coverboard or fire barrier. Those terms can hide substantial differences. A layer may absorb heat, delay heat transfer, physically interrupt flame penetration, retain support beneath a membrane or influence the pathway of degradation products.

The evidence should therefore distinguish **what happened** from **why it happened**. If less insulation is damaged, that is an outcome. Whether the difference resulted from thermal inertia, dehydration, physical continuity or another mechanism requires separate evidence.

## Integrity is not insulation

By analogy with the distinction between integrity and insulation in fire-resistance testing, direct flame penetration and thermal involvement should be treated as separate outcomes. European fire-resistance classification distinguishes loadbearing capacity (R), integrity (E), the ability of a separating element to resist the passage of flames and hot gases, and insulation (I), the limitation of temperature rise on the unexposed side. [41] A layer may continue to form a physical barrier while substantial heat is transferred through it. Kristensen and Jomaas provide a product-neutral example: beneath a mineral-wool protection layer the EPS did not ignite, yet it still melted through conductive heating. [3]

> **FUNCTION, NOT CLASSIFICATION**
>
> **This analogy describes a function, not a fire-resistance classification. No E, EI or REI classification follows from this distinction unless the construction has been tested and classified under the applicable fire-resistance standards.**

For reporting purposes, this paper therefore separates three criteria: flame integrity, whether direct flames remain above the protective layer; thermal transmission, how much heat reaches the materials beneath it; and damage propagation, how far melting, decomposition or combustion develop into the roof construction. A layer can perform well on the first criterion while the second and third remain significant.

## What has been demonstrated

The strongest generic evidence concerns modification of heat transfer. In the EUMEPS/IVH programme, a 12 mm cement-bonded particle board changed the behaviour of several PVC/EPS configurations and DBI interpreted the board principally as a heat sink. [9] Comparable 12 mm cement-bonded particle boards weigh approximately **19 kg/m²** depending on product density and commonly fall into A2-s1,d0 or B-s1,d0 classes rather than A1 because they contain wood particles. [42] Those classifications describe reaction-to-fire performance and should not be interpreted as evidence of the heat-sink mechanism discussed here.

Kristensen and Jomaas demonstrate a related protective function using different materials. Both mineral wool and PIR altered the thermal exposure reaching the EPS beneath them. [3]

Olsø, Haukø and Risholt provide supporting evidence outside the PV-roof field. Their protected-EPS experiments show that protective performance depends on material, thickness and duration rather than reaction-to-fire class alone. [43]

## Thermal buffering is not one property

The term *heat sink* should not be used generically. Thermal behaviour depends on areal mass, heat capacity, conductivity, moisture content, thickness and material transformation during heating.

Gypsum provides a clear example because chemically bound water absorbs energy during endothermic dehydration. Kontogeorgos and Founti describe this calcination process and its effect on heat transfer through gypsum board. [44]

A gypsum-based roof board illustrates the mass scale, with published values around **5.9 kg/m² at 6.4 mm**. [45] Commercial coverboards can also be cementitious products or high-density polymeric boards. [46,47]

FM defines coverboard as a board directly above the insulation and beneath the membrane and gives examples including a minimum 25 mm mineral-wool layer. [2] A representative rigid 25 mm mineral-wool roof support panel has a density around 176 kg/m³, corresponding to approximately **4.4 kg/m²** at that thickness. [48] This illustrates that a mineral-wool coverboard can also be relatively light. Weight alone therefore does not identify a particular fire mechanism.

## Physical separation remains assembly-specific

An intermediate layer can provide a physical discontinuity between surface fire and deeper combustible layers. These sources do not establish that every hard layer will prevent flame penetration under every PV exposure. Continuity, board joints, penetrations, fasteners, drains, rooflights and duration all matter.

Several additional mechanisms remain plausible rather than demonstrated. Maintaining mechanical support beneath a membrane above melting EPS is physically credible but has not been isolated experimentally. Restriction of combustible degradation gases through a sufficiently continuous sheet is also physically plausible.

The substrate evidence adds another mechanism: **the thermal boundary condition can change dynamically if EPS melts away from beneath the membrane**. That mechanism has been observed in conventional roof testing but has not been isolated under PV.

*Table 4. Evidence status of possible effects of an intermediate hard layer.*

| Possible effect | Status | Evidence boundary |
|---|---|---|
| **Delay of heat transfer into deeper roof layers** | DEMONSTRATED | Specific mineral-wool, PIR and board assemblies |
| **Heat-sink behaviour through thermal inertia of a dense board** | DEMONSTRATED | Heavy 12 mm board in EUMEPS/IVH |
| **Endothermic buffering from gypsum dehydration** | DEMONSTRATED at material level | Assembly-specific performance |
| **Limited thermal damage below a layer while surface fire continues** | DEMONSTRATED | Specific test assemblies |
| **Barrier against direct flame penetration while substantial heat transfer continues** | DEMONSTRATED | Specific assemblies; comparable with the integrity/insulation distinction but not an EN 13501-2 fire-resistance classification |
| **Change in thermal boundary condition as EPS melts away** | PHYSICALLY SUPPORTED for roof-PV use | Mechanism observed in conventional roof-covering tests, not isolated under PV |
| **Generic prevention of flame penetration by any hard sheet** | UNKNOWN GENERICALLY | Requires assembly evidence |
| **Retention of membrane support above melting EPS** | PHYSICALLY SUPPORTED | Not isolated experimentally |

| Possible effect | Status | Evidence boundary |
|---|---|---|
| **Restriction of degradation-gas pathways** | PHYSICALLY SUPPORTED | Not independently demonstrated generically |
| **Equivalent performance from boards with different mass or chemistry** | UNSUPPORTED | Evidence cannot be transferred by category |
| **Reduction of smoke or contaminated firefighting water** | UNKNOWN | No matched roof-PV comparison |
| **Performance after ageing and repairs** | UNKNOWN | Tests predominantly use new assemblies |

The useful specification is therefore functional rather than categorical:

> **FUNCTIONAL REQUIREMENT**
>
> **The roof-PV assembly should provide an evidenced interruption between the fire exposure above the membrane and deeper combustible construction for the intended materials, geometry, details and duration.**

# 7. Weight, thermal performance and roof-design trade-offs

## Structural capacity is a finite design resource

Fire performance is not the only constraint on a commercial roof. A roof-PV design must also accommodate insulation, waterproofing, mounting systems, PV modules, cables, maintenance loads and, depending on the system, ballast.

FM provides a useful order-of-magnitude reference. For PV on existing roofs, Data Sheet 1-15 recommends allowing approximately **0.10–0.14 kPa**, equivalent to roughly **10–14 kg/m²**, for PV modules and hardware before additional ballast. [2]

## Equal thermal performance can require very different mass

Published ArcelorMittal roof data provide a useful practical comparison. A roof using approximately **120 mm PIR** and another using approximately **200 mm stone wool** can achieve broadly similar U-values around 0.18 W/m²K. With representative densities, the stone-wool insulation represents approximately **24 kg/m²**, while 120 mm PIR around 30 kg/m³ weighs approximately **3.6 kg/m²**. [34,49]

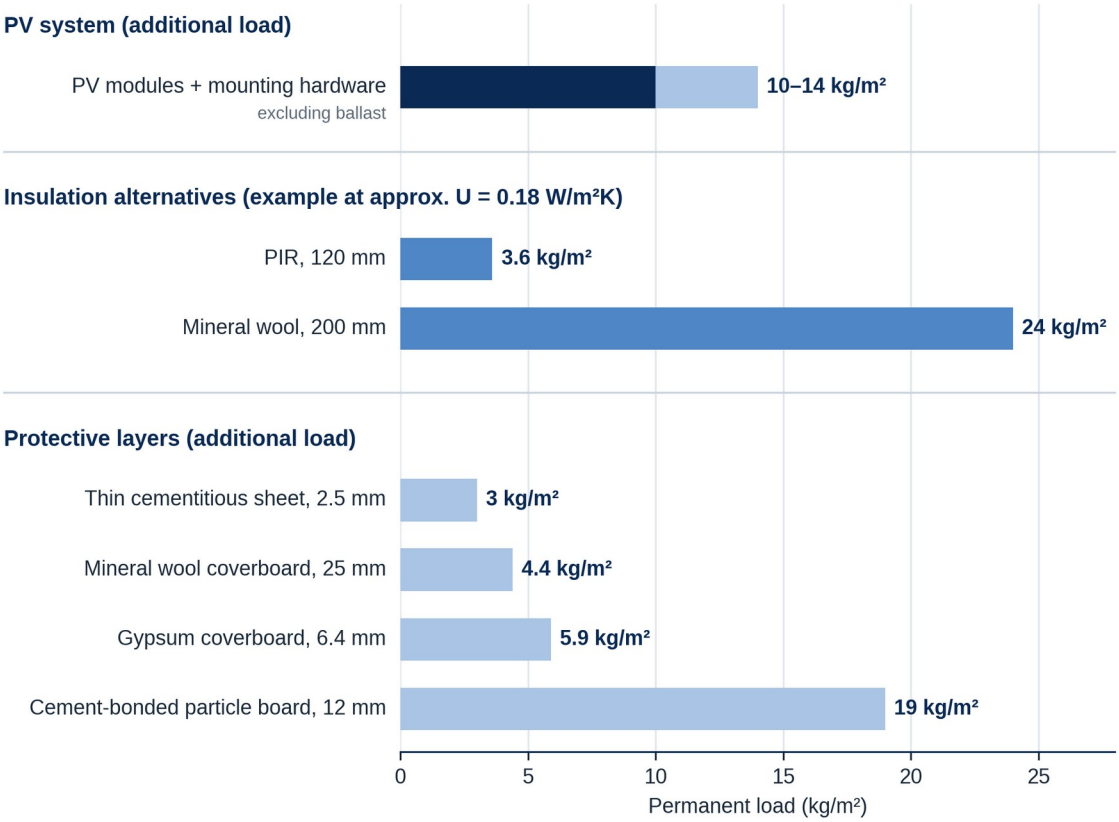
This is not a universal comparison. The purpose is to illustrate the order of magnitude that the difference can reach.

## A protective layer consumes structural reserve as well

Introducing a protective layer creates a second weight decision. Representative examples include:

- thin cementitious sheet, 2.5 mm: approximately **3 kg/m²**;
- 25 mm rigid mineral-wool support or coverboard: approximately **4–4.5 kg/m²**;
- 6.4 mm gypsum roof board: approximately **5.9 kg/m²**;
- 12 mm cement-bonded particle board: approximately **19 kg/m²**. [42,45,48]

These materials do not provide equivalent fire performance merely because their masses are known. The comparison is structural, not a ranking of fire protection.




Insulation alternatives replace each other; protective layers add load on top of the roof build-up.

*Figure 3. Illustrative permanent roof loads. Insulation alternatives replace one another while protective layers represent additional load.*

Dutch insurer guidance identifies the same structural issue from an operational perspective. The Dutch Association of Insurers warns that not every commercial roof was designed for the additional permanent load from PV and that deformation can impair drainage, allowing water to accumulate and further increase load. [50]

## Added mass does not necessarily provide useful insulation

A protection board can consume significant structural reserve while contributing little to the primary thermal resistance of the roof. The additional kilograms may therefore perform mainly mechanical and fire-related functions.

Mineral-wool protection can contribute to both thermal resistance and consequence limitation. Foam glass can combine insulation and non-combustibility. Gypsum contributes limited insulation but gains fire-protective behaviour from dehydration. Dense cementitious materials can provide thermal inertia and mechanical protection.

## More mass is not automatically more protection

Greater areal mass does not translate linearly into greater fire protection because chemistry, specific heat, thermal conductivity, moisture, joint behaviour and exposure duration all influence the result.

There is therefore no evidence basis for a universal “fire protection per kilogram” metric. The same evidentiary standard applies to a **3 kg/m² layer as to a 19 kg/m² board**. Low weight becomes a genuine engineering advantage only once the required consequence-limiting function has been demonstrated.

## New construction and retrofit pose different questions

New construction allows supporting structure and fire strategy to be designed together. Non-combustible insulation can therefore often be accommodated structurally from the outset.

Retrofit is different because the steel deck and supporting structure already exist, while the PV system itself can consume approximately 10–14 kg/m² before ballast. [2] Replacing lightweight PIR with mineral insulation or adding a heavy protection board can materially change feasibility.

The correct comparison is therefore between complete feasible routes rather than isolated materials. Adding insulation above an existing roof should not be treated as equivalent to replacing the existing insulation: retained layers remain part of both the structural and fire assessment.

## Temporary incident loads matter as well

Firefighting can create temporary load. Suppression water can accumulate on a roof whose capacity may already be affected by fire, PV dead load or deformation. FM requires this interaction with water loading and drainage to be considered where relevant. [2]

**DESIGN QUESTION**

**Which complete roof-PV assembly provides the required thermal, structural and consequence-limiting performance within the actual constraints of the building?**

# 8. Beyond flame spread: consequences poorly understood

## The consequence does not end when flame spread stops

Most roof-PV research measures flame distance, temperature, duration, penetration and visible material damage. For an asset owner or insurer, however, the loss continues beyond those metrics. Smoke can contaminate the building, firefighting water can transport combustion products, PV components can remain electrically hazardous, thermal damage can persist below apparently extinguished layers and module fragments can disperse beyond the roof.

**KEY POINT**

**Fire spread has been tested far more extensively than fire consequence.**

## Smoke depends on which materials become involved

Material studies show that fire effluent changes with the materials involved. PIR and PUR can produce CO and HCN, while PVC degradation can release HCl. [10–12,18] RIVM's work on fires involving solar panels found PAHs and metals including lead but concluded that PV modules are generally only one part of the total burning material in a substantial building fire. [51]

If a consequence-limiting assembly prevents some polymeric insulation from becoming involved, one source of potentially toxic fire effluent is correspondingly absent from that part of the fire. What is missing is a matched roof-PV experiment that quantifies the total smoke difference with and without the protective layer.

## Hidden thermal damage and smouldering are demonstrated mechanisms

Thermal activity can continue without visible flaming. Kristensen and Jomaas documented EPS melting beneath protection without ignition. [3] De Paula and colleagues observed smouldering associated with mineral-wool binder around joints. [12] Hidalgo, Torero and Welch examined oxidative smouldering of char formed by PIR and phenolic foam. [11]

The existence of a dedicated European method for continuous smouldering, EN 16733, further illustrates why post-flame behaviour should be considered separately from conventional reaction-to-fire classification. [16]

Leppänen and Malaska add another caution: a product-level open-flame smouldering test does not necessarily reproduce prolonged thermal exposure. [17] That distinction is directly relevant to rooftop PV because the cavity can subject the roof to continuing heat even after the initiating source has changed or disappeared.

The Kiwa/PU Europe programme provides a particularly clear example of prolonged thermal development after the visible fire. In the mineral-wool assembly, the temperature halfway through the insulation was approximately 35°C after 30 minutes but subsequently rose to approximately 185°C after 60 minutes, 343°C after 120 minutes, 403°C after 180 minutes and 440°C after 234 minutes, while still rising slowly. Overnight measurements recorded a peak of approximately 190°C at the steel deck. In the PIR assembly, the temperature halfway through the insulation increased more rapidly to approximately 155°C after about 23 minutes and subsequently declined to approximately 65°C after around two hours. The fire had deliberately not been extinguished in either test. [26]

This prolonged post-flame temperature development is relevant to the mechanism described by Leppänen and Malaska, who demonstrated that organic binder in mineral wool can contribute heat under sustained heating. [17] The Kiwa programme did not isolate the cause of the temperature rise, however, so it cannot establish that binder smouldering was responsible for the observed thermal history. The result should likewise not be generalised from this tested assembly to mineral-wool roofs as a class.

## Firefighter safety is broader than flame exposure

The TÜV Rheinland/Fraunhofer programme explicitly addressed firefighter safety including electrical risks and leakage currents associated with firefighting water around energised PV installations. [7] Dutch operational guidance similarly treats electrical isolation, roof access and structural conditions as part of PV incident response. [52]

NIPV investigated 70 building fires involving PV between November 2022 and October 2023. In six cases PV hindered fire behaviour or suppression, while in 30 cases, approximately **43%**, additional post-fire measures were taken to make the PV installation safe. [5] The dataset is small and primarily residential, so these percentages should not be interpreted as commercial-roof probabilities.

## Firefighting water is a measured environmental problem

The Fire Protection Research Foundation identifies firefighting runoff as an environmental pathway alongside atmospheric emissions. [53] Rogula-Kozłowska and colleagues analysed extinguishing-water runoff from small-scale furnishing-material fires and found major differences in toxicity between materials. [54] Trawińska and colleagues subsequently analysed runoff from ten real fire incidents and found high acute aquatic toxicity in many samples. [55]

These studies demonstrate that contaminated runoff is real. They do not demonstrate that a roof separation layer reduces water use or runoff toxicity.

## Water changes the incident as well as carrying contamination

Firefighting water is not only an environmental transport pathway. It is also part of the physical fire scenario. Water can cool the membrane, PV components and upper roof layers while at the same time entering damaged insulation, transporting soot and soluble degradation products and temporarily adding weight to the roof.

A hard protective layer may also limit direct access of water to material beneath it. That could be beneficial if deeper material never became involved, or problematic if hidden hot material remains difficult to cool. The reviewed evidence does not establish which effect dominates.

## PV fragments can carry the consequence beyond the building

RIVM documented sharp solar-cell fragments and residues containing metals and PAHs following fires involving PV. Its toxicological assessment concluded that one-off human exposure to the deposited chemical substances was generally of limited concern compared with the wider building fire, while the physical hazard from sharp fragments can be more practically relevant. [51]

Of the 31 investigated NIPV fires in which panels themselves were affected, 17 involved deposition of PV remnants and in 4 cases fragments were reported more than 100 m from the fire. [5] NIPV explicitly cautions that the dataset covers only one year and a limited number of incidents.

NIPV subsequently developed dedicated guidance for the post-fire phase. [56]

## Damage boundaries can extend beyond flame boundaries

For insurers, water, smoke and soot damage can be as significant as direct flame damage. Dutch insurance commentary explicitly identifies these wider forms of loss and their effect on continuity. [57]

A roof requiring replacement of modules and membrane over a local area is therefore a fundamentally different recovery problem from one requiring removal of membrane, insulation and damaged steel deck. Current PV fire testing rarely quantifies repair area, waste, reinstatement duration or business interruption.

This is where the final protection objective lies. Whether a local roof-PV fire becomes a building-scale loss depends on the roof build-up, but also on detection, fire-service access, compartmentation, roof size and how long operations are interrupted. No roof test demonstrates that outcome on its own; it can only be reasoned from the separate outcomes that tests do measure.

# 9. What this means for roof-PV design

## Begin with the consequence objective

The previous chapters lead to a design question that is broader than “which insulation is safest?” and narrower than “which fire product should be specified?”. The relevant objective is to prevent a rooftop PV fire from having an unnecessarily easy pathway from the membrane-level fire into deeper combustible roof construction and ultimately into the building.

In practice, that objective becomes a decision question for the designer, owner and risk engineer: which damage below the PV array is acceptable, and what keeps flames out of the combustible insulation? Answering it requires an explicit acceptance level for each outcome distinguished in Chapter 1, rather than one pass or fail label for the roof as a whole.

This distinction matters because the evidence does not identify one universally superior roof build-up. A non-combustible roof can remove combustible insulation fuel while still permitting a membrane fire. A protective layer can limit downward involvement while leaving combustible material above and below it. A lightweight construction can preserve structural capacity while still requiring representative fire evidence.

## Prevention and consequence limitation perform different functions

Electrical design, workmanship, inspection and maintenance reduce the probability of ignition. Roof construction determines what happens if those controls fail and sustained fire occurs. FM and the insurer-supported RC62 guidance both treat prevention and mitigation as complementary measures rather than substitutes. [2,58]

## New roofs and existing roofs require different strategies

For new construction, non-combustible insulation can remove a major combustible fuel source from the downward escalation pathway. The ZAG/FRISSBE guideline identifies this as its primary recommendation where practical. [8]

Existing roofs present a different problem. Where replacement of combustible insulation with a non-combustible build-up is practical, that removes a fuel pathway directly. Where replacement is not feasible, the next question is whether the retained combustible construction can be placed behind an **evidenced consequence-limiting assembly**.

## Replacement, overlay and separation are different strategies

Replacing combustible insulation with non-combustible insulation removes a combustible fuel source from the roof construction. Adding a non-combustible layer above retained combustible insulation does not achieve the same thing: the original fuel remains present, while the added layer may delay, redistribute or otherwise modify the thermal exposure reaching it. The resulting roof should therefore be assessed as a new layered assembly rather than treated as equivalent to a roof in which the combustible insulation has been removed.

A dedicated separation layer serves a different primary function again. Its purpose is to introduce an evidenced discontinuity in the downward fire pathway close to the exposed roof surface. Depending on its material properties, thickness and mass, it may also influence heat transfer or membrane-level fire behaviour, but those effects require their own evidence. Physical continuity against direct flame penetration and thermal buffering are therefore related but different functions.

Position matters because protection can only act on the fire pathway that lies beyond it. In conventional separating construction, a protective layer is positioned between the fire exposure and the material to be protected. In a rooftop PV fire, the waterproof membrane is itself part of the exposed fire system and lies above a separation layer installed beneath it. Such a layer may therefore protect deeper construction without removing the membrane fuel or guaranteeing that fire above it will cease.

Increasing the thickness of a protective overlay can improve the delay and thermal protection provided to deeper layers, but it does not remove combustible material that remains above or below it. Nor does greater thickness alone demonstrate reduced membrane-level propagation: Chapter 3 shows that this also depends on thermal inertia, conductivity, material transformation and the PV-modified exposure.

These strategies should therefore not be compared only by added insulation value or reaction-to-fire classification. For an existing roof, the relevant comparison is between complete feasible assemblies: what combustible material remains, what interrupts direct flame penetration, how much heat can still reach the retained construction and what additional mass, thickness and detailing the intervention introduces. Where additional thermal insulation is required, an insulation upgrade and a dedicated separation function are not mutually exclusive.

For FM-insured locations, modifying an existing roof is not automatically equivalent to an approved roof-PV assembly. FM calls for project plans and specifications to be submitted for review and defines specific acceptable routes for existing roof covers that remain in place. An insulation overlay or re-cover should therefore be assessed within the resulting complete assembly rather than assumed acceptable because the added material itself has a favourable fire classification. [2]

Two FM routes should therefore be kept apart. For new construction, a project can often be designed directly around a complete FM Approved RoofNav assembly. Existing-roof projects are inherently more project-specific, because the retained deck, existing roof layers, attachment and condition become part of the engineering assessment. A RoofNav recover assembly may provide the approved basis, but FM still has to assess whether the actual existing construction and any deviations are acceptable for that project. Individually approved components do not by themselves form an approved assembly.

## The membrane and PV geometry remain inside the design problem

A protection layer beneath the membrane cannot remove fuel above it. Membrane type, thickness and attachment therefore remain relevant even when deeper insulation is protected.

The PV array itself also belongs within the fire strategy. Gap height, inclination, module spacing, array layout and wind can materially alter the fire environment. [1,22,25,30]

## Evidence should match the intended assembly

Different forms of fire evidence answer different questions. The most important difference is often the direction and nature of the exposure.

*Table 5. What different fire classifications and tests answer.*

| Evidence / classification | Exposure | What it answers | What it does not answer |
|---|---|---|---|
| **Euroclass, EN 13501-1** | Defined reaction-to-fire exposure of a product | How the product contributes to fire growth, heat release, smoke and droplets under the applicable tests | Behaviour of the complete roof beneath PV |
| **BROOF(t1), EN 13501-5 / CEN/TS 1187** | Defined external fire exposure of a roof from above | External-fire performance of the tested roof system | Behaviour under every PV cavity, geometry or prolonged exposure |

| Evidence / classification | Exposure | What it answers | What it does not answer |
|---|---|---|---|
| **REI, EN 13501-2 / EN 1365-2** | Standardised fire-resistance exposure of the tested element; for roofs normally from the underside | How long the tested construction maintains R, E and/or I under that defined test | Equivalent protection against a rooftop PV fire developing above the membrane |
| **Roof-PV fire test** | Fire exposure beneath PV, above the roof membrane | Behaviour of the tested PV-roof assembly in that defined configuration | A formal Euroclass, BROOF or REI classification unless separately established |

A roof classified REI 60 has demonstrated 60 minutes of the specified R, E and I performance under the prescribed fire-resistance test, with fire exposure from below. [41,59] It does not mean that the same roof will provide 60 minutes of equivalent protection against a rooftop PV fire developing from above. A roof with a fire-resistant concrete deck can still carry combustible insulation and membrane that burn from the top. Conversely, the absence of an REI classification does not determine how that roof will behave under PV. These forms of evidence are not interchangeable.

German guidance gives a related scope warning. The Fachkommission Bauaufsicht's Merkblatt of 8 May 2026 states, below §2.2, that knowledge is lacking on whether DIN 18234 roofs continue to meet MIndBauRL 2019 §5.13 after PV is added. This is an evidence gap, not a finding that every such roof fails. Sections 2.2 and 2.3 address array subdivision and firefighting access; their further measures should not be recast as a general demand for additional fire tests. [68]

If a design relies on a protective layer over combustible insulation, evidence should be relevant to the membrane, layer, insulation, deck, PV geometry and critical details intended for the project.

## Details and service life matter

Rooflights, penetrations, drains, parapets, expansion joints, mechanical fixings and transitions can interrupt a protective plane.

The same principle extends over time. Operational roofs experience UV exposure, thermal cycling, maintenance traffic, repairs and joint movement. A consequence-limiting strategy should therefore remain inspectable and maintainable.

## Guidance, approval and regulation should not be conflated

FM Property Loss Prevention Data Sheets are insurer loss-prevention guidance. FM Approvals apply to specified products and assemblies under defined conditions. RC62 is an insurer-supported Joint Code of Practice. ZAG/FRISSBE is technical guidance. OFR's literature review was commissioned by the UK Building Safety Regulator but does not itself create regulatory requirements. [1,2,8,58]

The Dutch regulatory baseline illustrates the distinction. Article 4.47 of the *Besluit bouwwerken leefomgeving* requires the upper surface of a roof to be non-fire-hazardous as determined according to NEN 6063. [60] It does not impose a general requirement that commercial flat-roof insulation must be non-combustible. The NEN 6060 working group identifies the interaction between PV and roof construction above large fire compartments as an issue in the revision process. [61]

## A system-based design check

*Table 6. System-based design check for a roof-PV project.*

| Design question | Required engineering answer |
|---|---|
| **1. Can ignition probability be reduced?** | Apply competent electrical design, connector control, installation, inspection, maintenance and monitoring. |
| **2. What happens if ignition still occurs?** | Assess the PV-modified membrane-level exposure. |
| **3. Can combustible insulation be avoided?** | Prefer removal of a major combustible fuel source where technically and structurally practical. |
| **4. If combustible material remains, what interrupts the fire pathway?** | Require an evidenced consequence-limiting assembly. |
| **5. What combustible material remains above the protective plane?** | Include membrane, adhesives and exposed roof materials. |
| **6. Can the protective function be bypassed?** | Assess joints, anchors, drains, rooflights, penetrations, edges and transitions. |
| **7. Is the complete design structurally feasible?** | Verify PV mass, ballast, insulation, protection layers, wind, snow, drainage and temporary incident loads. |
| **8. Does the evidence match the proposed assembly?** | Do not transfer test results to materially different systems without justification. |
| **9. Will the intended protection still exist through service life?** | Document, inspect and maintain critical details. |
| **10. Is combustible insulation being removed or only covered?** | Distinguish fuel removal from an overlay or separation strategy and assess all retained layers as part of the complete roof-PV assembly. |

## Product-neutral specification principle

**SPECIFICATION PRINCIPLE**

**For rooftop PV installed above a commercial flat roof, provide an evidenced consequence-limiting roof-PV strategy that limits downward fire escalation from the PV-modified membrane-level fire into deeper combustible construction and validate that strategy for the intended complete assembly.**

# 10. BarrierSheet as one case study

## Applying the same standard to the author's own product

The first nine chapters establish the design criteria before considering an AllShield product. The commercial relationship is direct: the author is employed by AllShield, ZAG Report 448/25-560-1-EN identifies AllShield Holding BV as the orderer of the test programme, the Efectis test and classification programmes were sponsored by AllShield Coatings BV and FM Approval Report PR472014 concerns approval of AllShield BarrierSheet. [62–66]

BarrierSheet itself is a formulated cementitious coverboard. FM documents the current product at **2.5 mm thickness**, while Efectis specimen data give an areal mass around **3.0 kg/m² ±10%**. [63,64]

This makes the product materially different from a 12 mm, approximately 19 kg/m² cement-bonded particle board. The heat-sink evidence for the latter cannot therefore be transferred automatically to BarrierSheet.

## What the ZAG programme actually tested

ZAG Report 448/25-560-1-EN examined four roof-PV configurations at approximately 2.5 × 2.5 m and 3.5 × 4 m scale. AS-1 used a TPO membrane (Sarnafil TS 77-18) and AS-2 to AS-4 a PVC membrane (Sikaplan G-18). In all four, a single anchored layer of BarrierSheet was installed over bitumen on 100 mm EPS; AS-2 and AS-4 added 60 mm and 120 mm PIR respectively between BarrierSheet and the bitumen. AS-1 and AS-3 therefore represent a renovation case in which BarrierSheet and a new membrane are laid directly over a retained bituminous roof on EPS. [62]

The ignition challenge was increased when a single enlarged wood crib failed to produce sustained propagation. ZAG subsequently used two enlarged cribs. The resulting double-crib exposure was estimated at around **40 kW**, with explicit uncertainty. [62]

In every run considered successfully ignited by ZAG, flames travelled across the PV-covered area.

The programme therefore does **not** demonstrate that BarrierSheet prevents membrane-level propagation beneath PV. Its strongest finding concerns a different level of the fire pathway:

> **ZAG FINDING**
>
> **ZAG concluded that BarrierSheet prevented direct flame penetration into deeper structural layers in all tested configurations, during the documented test periods. [62]**

ZAG itself distinguishes these observations. It describes the localised gaps and burn-through areas as allowing some heat transfer to materials in deeper layers, while concluding that direct flame penetration into those layers was prevented. [62] Local loss of sheet integrity nevertheless remains relevant to joints, fixings and exposure beyond the documented test periods.

## The first AS-3 run is an important qualification

The initial AS-3 run used one enlarged crib. Fire did not propagate beyond the ignition area and extinguished after the crib burned out, yet post-test inspection found damage through the layered roof over an area of approximately **20 cm²**, extending to the EPS. Bitumen and EPS immediately beneath the ignition area had melted completely. [62]

This observation separates horizontal propagation from local depth of damage. Limited surface spread did not mean limited local thermal involvement.

## No flame penetration did not mean no thermal involvement

Peak measured temperatures immediately beneath BarrierSheet ranged from approximately **430°C to more than 800°C** across the ZAG configurations. [62] EPS melted through its full 100 mm thickness in parts of AS-1. PIR configurations showed deformation, decomposition products and damage extending significantly into the insulation.

**INTERPRETATION**

**Surface propagation occurred; direct flame penetration into deeper structural layers was prevented; substantial thermal involvement below BarrierSheet still occurred.**

By analogy with the functional distinction between integrity and insulation introduced in Chapter 6, the ZAG result is primarily a barrier result: direct flame penetration into deeper structural layers was prevented while substantial thermal transfer and thermal involvement below the sheet still occurred. This analogy does not constitute an E, EI or REI classification. The ZAG programme was not an EN 1365-2 fire-resistance test and no EN 13501-2 fire-resistance class follows from it. [41,59]

## Joints and anchors are part of the fire performance

The ZAG programme identified damage associated with board joints and anchorage. In AS-2, ZAG recorded localised burn-through of the sheet together with gaps between adjacent boards, which may have facilitated localised heat transfer. In AS-4, gaps developed at joints although the sheet largely maintained its shape. Mechanical restraint at fixings influenced thermal deformation. [62] Together with the initial AS-3 run, localised burn-through of the sheet was therefore recorded in two of the four configurations. ZAG's overall conclusion on direct flame penetration and these localised observations should be read together.

BarrierSheet should therefore not be understood as a material property alone. Its function depends on installation continuity, joint treatment and the complete layered construction.

## The 100°C plateau may indicate moisture-related buffering

ZAG observed a temperature plateau around **100°C** below BarrierSheet and suggested that evaporation of moisture or bound water may have contributed to the temperature response. [62] If evaporation contributes, part of the temporary buffering would arise from the latent heat of vaporization.

The magnitude of that contribution was not isolated experimentally. The appropriate evidence status therefore remains **PHYSICALLY SUPPORTED**.

## A low-mass sheet should not borrow a heavy-board mechanism

The EUMEPS/IVH programme suggests that a relatively heavy 12 mm cement-bonded particle board can act as a heat sink at membrane level. [9] BarrierSheet is approximately 2.5 mm thick and around 3 kg/m², so substantially less thermal mass is available to absorb energy than in the approximately 19 kg/m² reference board discussed in Chapter 6.

A **PHYSICALLY SUPPORTED** explanation for the difference between the EUMEPS heavy-board observations and the ZAG BarrierSheet observations is therefore that the thin sheet provides less heat-sink capacity at membrane level. This would be consistent with ZAG showing continued membrane-level propagation while BarrierSheet still prevented direct flame penetration into deeper structural layers.

The mechanism was not isolated by ZAG and should not be presented as demonstrated. The evidence supports a **barrier function against direct flame penetration**, not equivalence with the heat-sink behaviour of a much heavier board.

## The programme does not quantify improvement

Every ZAG configuration contained BarrierSheet. There was no otherwise identical reference roof without the product. The programme can therefore state what happened **with** BarrierSheet but cannot quantify the improvement caused by adding it.

It cannot support a percentage reduction in flame spread, damaged insulation mass, smoke production, runoff or total loss relative to a matched unprotected roof.

## FM Approval remains assembly-specific

BarrierSheet is FM Approved under **FM 4470 and FM 4478** through Approval Report PR472014, dated 11 December 2025. [63] One listed implementation is RoofNav assembly **568563-0-0**.

This is strong evidence for a particular approved implementation of the current 2.5 mm product. It is not blanket approval for arbitrary roof constructions.

Approval Report PR472014 also documents ASTM E108 spread-of-flame testing of one layer of the current 2.5 mm BarrierSheet beneath a mechanically fastened TPO membrane (Sarnafil TS 77-15), on 50 mm PIR insulation and a plywood deck. Two samples passed Class A at a slope of 0.5 in 12. The assembly was tested without PV. The result is evidence of external-fire performance for that specified single-layer assembly; it is not a BROOF(t1) classification, not a roof-PV fire test and not an approval for existing roofs. [63]

## The Efectis test used two BarrierSheet layers

Efectis Report 2025-Efectis-R000982 tested the following construction: **PVC membrane → 2.5 mm BarrierSheet → 140 mm PIR → 2.5 mm BarrierSheet → PE foil → steel deck**. BarrierSheet was therefore used **both above and below the PIR**. [64]

## Two formal classifications are documented

Efectis subsequently classified this roof construction **BROOF(t1)** under EN 13501-5:2016. [65] The direct field of application is the tested construction: 1.5 mm polyester-reinforced PVC, BarrierSheet under and above 140 mm PIR, a PE vapour barrier and a steel deck, at roof pitches of 0–20°. An extended field of application under CEN/TS 16459 additionally covers, among other parameters, BarrierSheet of at least 2.5 mm and 2.7 kg/m², PIR of class B-s1,d0 or better with the same or lower compressive strength and steel decks of at least 0.4 mm. The number of layers remains as tested, and the report notes that the extended field of application is not part of its accredited section under Dutch regulations. [65]

A roof containing only one BarrierSheet above the PIR therefore remains outside both the tested configuration and this classification unless separate evidence covers it.

Whether roofs with a TPO or bituminous membrane fall within the extended field of application has not been established here and is treated as open.

BarrierSheet itself is classified **A1** for reaction to fire under EN 13501-1:2018, for a thickness of 2.5 mm and a surface density of 3.0 kg/m². The product is non-homogeneous and the classification is based on EN ISO 1716 and EN ISO 1182 results and covers the two top-layer variants tested. [66] As Chapter 2

and Table 5 explain, this is a classification of the material's own contribution to fire. It does not describe roof-PV system behaviour and is distinct from fire resistance.

## Earlier Kiwa-BDA evidence concerns an earlier product thickness

An earlier Kiwa-BDA programme examined a roof-PV construction using **1.2 mm BarrierSheet**, rather than the current 2.5 mm product. Kiwa-BDA report 24L0241/1, dated 2 September 2024, should therefore be treated as development-history evidence rather than as testing of the current product thickness. [67]

Although this programme concerns the earlier 1.2 mm BarrierSheet configuration and only 50 mm PIR, it provides direct within-test evidence that damage did not extend equally far through all layers. Kiwa concluded that the extent measured in the thermal insulation beneath the barrier was approximately 40% lower than above the barrier in Test 1 and approximately 30% lower in Test 2. The fire barrier itself was damaged over much of the membrane damage footprint, while the extent in the insulation was smaller. This is a within-assembly comparison, not evidence of a 30–40% improvement relative to an otherwise identical roof without BarrierSheet. [67]

## Low weight is an advantage, not a fire mechanism

At approximately 3 kg/m², BarrierSheet imposes substantially less permanent load than many conventional protection boards. That can be relevant on lightweight existing commercial roofs.

However, mineral-wool coverboards can also be relatively light. A representative 25 mm rigid mineral-wool support panel can be in the order of 4–4.5 kg/m². [48] BarrierSheet should therefore not be positioned as though it is the only lightweight protective option.

Low mass is a structural characteristic, not evidence of fire performance.

BarrierSheet should therefore not be compared with an insulation overlay solely on the basis of added thermal resistance. The interventions may serve different primary functions. An insulation overlay changes the thermal build-up and may also provide fire protection where demonstrated, while the strongest current BarrierSheet evidence concerns interruption of direct flame penetration into deeper construction. Thermal transfer through the sheet can still be substantial.

## Evidence summary

*Table 7. Evidence status of BarrierSheet propositions.*

| BarrierSheet proposition | Evidence status | Boundary |
|---|---|---|
| **Current product is a 2.5 mm cementitious coverboard** | DEMONSTRATED | Documented: FM and Efectis |
| **Approximate mass is 3.0 kg/m²** | DEMONSTRATED | Documented: Efectis |
| **Prevented direct flame penetration into deeper structural layers** | DEMONSTRATED | ZAG configurations and documented test periods; localised burn-through in AS-2 and initial AS-3 |
| **Prevented membrane-level propagation beneath PV** | CONTRADICTED | Fire propagated across PV-covered area |
| **Prevented all thermal damage below the sheet** | CONTRADICTED | EPS melting, PIR decomposition |
| **Prevented local thermal damage through all layers** | CONTRADICTED | Initial AS-3 |
| **Damage in the insulation extended over a shorter length than on the membrane** | DEMONSTRATED | ≈30–40% less within the two 1.2 mm tests; no unprotected reference; 50 mm PIR configuration |
| **Functions primarily as a heat sink** | UNKNOWN | Mechanism not isolated |

| BarrierSheet proposition | Evidence status | Boundary |
|---|---|---|
| **Lower heat-sink capacity than a heavy board may explain continued surface propagation** | PHYSICALLY SUPPORTED | Difference in thermal mass, no matched experiment |
| **Moisture contributes to buffering** | PHYSICALLY SUPPORTED | 100°C plateau |
| **Performance independent of joints and anchors** | CONTRADICTED | ZAG joint and anchorage effects; gaps at joints in AS-2 and AS-4 |
| **FM Approved for roof-PV use** | DEMONSTRATED | Formally covered: Specified assemblies only |
| **Reaction-to-fire classification A1** | DEMONSTRATED | Formally covered: Efectis 2026-R000318; 2.5 mm, approximately 3.0 kg/m² BarrierSheet |
| **BROOF(t1) classification** | DEMONSTRATED | Formally covered: Efectis 2025-R000983; within the stated field of application of the tested two-BarrierSheet PVC/PIR construction, 0 –20° pitch |
| BROOF(t1) performance of a single BarrierSheet layer above PIR | UNKNOWN | Not formally covered by R000983: two layers remain as tested. Any single-layer application is engineering extrapolation unless separately evidenced; absence of coverage is not evidence of failed performance. |
| **One layer of the current product achieved an external-fire class in a specified assembly** | DEMONSTRATED | ASTM E108 Class A, FM PR472014; TPO on 50 mm PIR, plywood deck, no PV; not BROOF(t1) |
| **BarrierSheet reduces flame spread by a defined percentage compared with an otherwise identical roof without the sheet** | UNKNOWN | No matched unprotected control |
| **Has demonstrated E, EI or REI fire-resistance performance** | UNKNOWN | Reviewed ZAG, Kiwa, Efectis and FM evidence does not constitute an EN 13501-2 fire-resistance classification |
| **Reduces toxic smoke** | UNKNOWN | No matched comparison |
| **Reduces contaminated runoff** | UNKNOWN | No matched comparison |
| **Reduces repair area or business interruption** | UNKNOWN | No matched comparison |
| **Makes combustible insulation equivalent to non-combustible insulation** | CONTRADICTED | Combustible insulation remains thermally vulnerable |
| **Makes arbitrary roof-PV assemblies fire safe** | UNKNOWN | Evidence is assembly-specific |

## The product case is consequence limitation, not fire elimination

The present evidence does not support describing BarrierSheet as a product that prevents PV ignition, stops all horizontal fire propagation or keeps combustible insulation outside the fire scenario.

What it supports is more precise. BarrierSheet formed a lightweight physical layer that, in the ZAG configurations examined, remained sufficiently intact to prevent direct flame penetration into deeper structural layers even while fire propagated above it and substantial thermal damage occurred below.

BarrierSheet is therefore one evidenced implementation of consequence-limiting design. It is not evidence that a combustible roof becomes equivalent to a fully non-combustible roof.

# 11. What remains unknown

## A stronger evidence base still has large blind spots

Rooftop-PV fire research has advanced rapidly. The field now understands considerably more about cavity effects, membrane propagation, insulation behaviour and protective layers than it did a decade ago. The evidence nevertheless remains strongest for **fire behaviour during a defined test** and considerably weaker for total consequence after and below that test.

Matched control experiments remain uncommon. Kristensen and Jomaas did **not include an unprotected reference**. [3] The ZAG BarrierSheet programme contained no otherwise identical specimen without BarrierSheet. [62] The EUMEPS/IVH programme contained a baseline but changed additional variables across parts of the series. [9] The separate Kiwa programmes commissioned by PU Europe and AllShield provide useful evidence on different roof-PV assemblies, but differences in insulation thickness, PV modules, glass condition, wind, instrumentation and other construction details mean that they cannot be treated as matched control experiments. [26,67]

## Accessible fire load remains largely conceptual

Chapter 5 distinguished total combustible material from the portion actually involved. The distinction is physically useful but poorly quantified. Most PV-roof tests measure temperature, flame distance or visual damage. Few quantify the mass of insulation that melted, decomposed or burned.

The concept of **accessible fire load** is therefore not yet a standardised metric.

## Surface propagation, penetration and thermal involvement need common reporting

Existing studies frequently use *fire spread* as a broad term even when they measure different phenomena. The evidence reviewed here shows why three separate outcomes are needed: **surface propagation, direct flame penetration and thermal involvement in depth**.

A common reporting framework using all three outcomes would make different programmes considerably easier to compare.

## Duration and post-flame behaviour remain poorly characterised

Protection is time-dependent. Kristensen and Jomaas demonstrated prolonged delay followed by eventual penetration of a PIR mitigation layer. [3] ZAG recorded significant subsurface heating during multi-module exposures. [62]

Continuous smouldering itself is not an unstandardised phenomenon. EN 16733 provides a product-level method for assessing propensity to undergo continuous smouldering after an open-flame exposure. [16] However, Leppänen and Malaska concluded that such exposure does not reproduce prolonged heating conditions. [17]

What remains poorly characterised for rooftop PV is therefore twofold:

1. how product-level smouldering propensity translates into a complete roof assembly;
2. how that assembly behaves under the sustained thermal exposure that can develop beneath a PV field.

The post-flame phase is therefore a system question, not only a material-classification question.

## Smoke, runoff and firefighter benefit remain largely unquantified

No matched rooftop-PV programme reviewed here has quantified how a separation layer changes total smoke toxicity.

The evidence gap is even larger for firefighting runoff. Toxic firefighting water is demonstrated in wider fire research. [53–55] No comparable roof-PV study has quantified water use or contamination with and without a protective layer.

PV also creates established electrical, access and safe-making challenges. [5,7,52] A roof that prevents deeper involvement may plausibly simplify the incident, but no reviewed study quantifies that operational advantage.

## Repairability may become one of the most important metrics

Replacement of modules and membrane is a fundamentally different loss from replacement of membrane, insulation and structural deck. Existing test programmes rarely quantify repair area, damaged mass, waste, drying time, reinstatement time or business interruption.

For asset protection these may ultimately become more useful metrics than flame distance alone.

## Ageing remains largely outside the evidence

Most fire specimens are new. Operational roofs experience UV exposure, thermal cycling, maintenance traffic, repairs, joint movement and penetrations added after construction.

Chapter 3 showed that membrane properties change with age. [27,28] Equivalent long-term evidence for protective layers is limited.

## Product-specific gaps illustrate a wider research problem

Chapter 10 illustrates the same evidence problem at product level. BarrierSheet has demonstrated specific behaviour in defined ZAG, FM and Efectis assemblies, while matched controls, mechanism isolation, ageing, smoke, runoff and recovery consequences remain unresolved.

> **RESEARCH RULE**
>
> **These are not unique weaknesses of one product. They illustrate a broader rule: compatibility, classification and demonstrated system fire performance are different claims.**

## Unknown does not mean ineffective

An evidence gap is not evidence that an effect does not exist. The absence of smoke data does not show that limiting insulation involvement has no smoke benefit. The absence of runoff measurements does not show that consequence limitation has no environmental benefit.

It means only that the corresponding claim has not yet been established. **DEMONSTRATED** should remain restricted to measured outcomes. **PHYSICALLY SUPPORTED** should describe mechanisms supported by physics but not demonstrated in the relevant assembly. **UNKNOWN** should remain unknown until evidence changes its status. Formal coverage and project-specific acceptance are routes and decisions, not changes in the status of the claim.

# Conclusion

Rooftop PV changes the fire environment of a commercial roof. The module-to-roof cavity can increase heat feedback and accelerate propagation, while membrane, wind, insulation, geometry and the material directly beneath the waterproofing can all influence the outcome.

The research also shows that **surface propagation, direct flame penetration and thermal involvement are different outcomes**. A roof can experience extensive fire beneath a PV array while deeper insulation remains only locally affected. Conversely, intense local heating can damage every layer beneath a relatively small fire footprint.

The material directly beneath the membrane is part of this system. A dense board can absorb thermal energy through thermal inertia. An effective thermal insulator may remove relatively little heat from the membrane. An aluminium facing may temporarily reduce radiative absorption. EPS can melt away and change the thermal boundary beneath the membrane. The PV panel itself can redirect and reradiate heat back towards the roof. These mechanisms should not be reduced to a simple combustible-versus-non-combustible comparison.

That does not reduce the importance of non-combustible insulation. Where new roofs can be designed from first principles, removing a major combustible fuel source from the deeper roof construction reduces the fuel available for escalation, while the complete roof-PV system still needs assessment. Where existing lightweight roofs constrain that option, alternative protective assemblies can have a legitimate engineering role provided that their performance is demonstrated for the intended complete roof-PV system.

Protective construction can influence whether, when and over what area deeper material becomes accessible to the fire. It does not remove fuel above the protective layer and it does not turn combustible insulation into non-combustible material.

> **FUNCTIONAL REQUIREMENT**
>
> **Interrupt the downward fire pathway and demonstrate that interruption in the intended roof-PV assembly.**

BarrierSheet is one case study of that principle. Its current evidence is strongest for prevention of direct flame penetration in specified configurations, not for elimination of membrane fire, heat transfer or thermal damage. Its low mass is structurally relevant but does not justify transferring the heat-sink mechanism demonstrated for much heavier boards.

The wider research challenge is now to move beyond flame spread towards measurable total consequence: involved material mass, hidden heating and smouldering, smoke, runoff, firefighter conditions, repairability and recovery.

> **CENTRAL QUESTION**
>
> **The relevant question is how far a rooftop PV fire is allowed to travel into the roof before it becomes a building loss.**

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# Method and sources

This is a targeted inventory and synthesis of identified knowledge, updated through the checks documented for 1 November 2026. It does not claim exhaustive coverage of the latest literature. Source findings, author analysis and practical design proposals remain distinct. The author endorses the conclusions within these evidence boundaries.

## Authorship and contributions

Olivier Langejan is the lead author, supported by a small team. His professional focus is building and roof design. The papers synthesise the cited research, standards and test evidence; specialist fire-science and electrical findings are attributed to those sources rather than presented as expertise personally established across every discipline. The author endorses the synthesis and its stated limits. AI assistance is described separately below.

## Key source boundaries

Approval Report PR472014 (11 December 2025), §§1.3, 3.2 and 9, identifies the applicable standards and evaluated assemblies and refers to RoofNav for the listing. The programme uses previous test data and waivers, including the 4478 external-fire requirement based on 4470 evidence. It does not document a new fire test with PV. Approval of a listed assembly and project-specific engineering acceptance are distinct decisions.

ZAG Report 448/25-560-1-EN, summary p. 3 and conclusion p. 46, reports prevention of direct flame penetration into deeper structural layers in the tested configurations during the documented test periods. Heat transfer, local gaps or burn-through and damage to underlying insulation were also recorded. These observations do not mean that all underlying layers remained undamaged. The programme has no unprotected reference from which a quantified reduction in risk can be calculated.

### Scope and selection

This paper synthesises surface spread, direct flame penetration and thermal involvement of deeper layers in commercial roof-PV fires. Experimental roof-PV research, related material studies and institutional guidance are included where they explain a mechanism. Results from adjacent fields are identified as such. This paper does not rank all commercial systems or validate a single universal protective layer.

### Sources and dates

The evidence base is the research, standards, approval documents, technical guidance and incident material identified in the references. This is a targeted narrative synthesis, not a systematic review. English-language sources and relevant Dutch or German material are included where cited. The original search dates and a complete search log are not available in the retained publication record, so no reconstructed search period or exhaustive publication cut-off is asserted. Sources retain their individual publication dates. The present editorial and targeted source checks were completed on 1 November 2026.

### Publication range

Publication dates and editions are identified for the individual references. This targeted synthesis does not claim exhaustive chronological coverage or a reconstructed complete search period.

## Verification

This revision checked the requested wording against the source papers and carried out targeted primary-source checks for the additions and source corrections identified in its revision history. It is not a new claim-by-claim audit of the entire paper. References identify primary documents where available; secondary accounts and access limitations are identified where material. Author interpretations and design proposals do not acquire test or approval status.

## Known gaps

Full Kiwa reports and the underlying DBI analysis of the EUMEPS/IVH campaign were not obtained in this revision; that discussion remains dependent on secondary reporting. Matched controls, long-duration response and quantified wider consequences remain limited.

## AI-assisted research and writing

Artificial intelligence was used to help identify and locate technical literature, compare findings across sources, analyse evidence boundaries, organise the argument and assist with drafting and editing. AI-generated summaries were not treated as technical evidence. The selection of sources, interpretation of the evidence, conclusions and final wording remain the responsibility of the author.

## Updates

New research, test results, incidents and regulation may lead to new versions. Editorial corrections and technical additions are identified separately in the revision history. Missing sources and evidence that challenges a conclusion are welcome.

## REVISION HISTORY

| Version | Date | Changes |
|---|---|---|
| **1.0** | 1 October 2026 | First complete version of Beyond flame spread. |
| **1.1** | 1 October 2026 | Added the Kiwa BDA / PU Europe comparative mineral-wool/PIR roof-PV programme as primary evidence. Expanded discussion of prolonged post-fire thermal development and clarified the within-test evidence from the earlier 1.2 mm BarrierSheet programme. No quantitative comparison between the separate programmes is made. |
| **1.2** | 2 October 2026 | Added a brief explanation of what Euroclass reaction-to-fire classification measures (SBI test, FIGRA, THR600s) and clarified that the classification of cement-bonded particle board is not evidence of heat-sink behaviour. |
| **1.3** | 10 October 2026 | Added the distinction between integrity and insulation as a conceptual framework for direct flame penetration versus thermal involvement. Clarified the different questions answered by Euroclass, BROOF, REI and roof-PV testing and explicitly separated BarrierSheet test evidence from formal fire-resistance classification. |
| **1.4** | 10 October 2026 | Added formal A1 and BROOF(t1) classification evidence for BarrierSheet. Distinguished insulation replacement, overlay and dedicated separation as different retrofit strategies and clarified how layer position, retained fuel and thermal function affect their interpretation. Added FM context for modifications to existing roofs. |
| **1.5** | 21 October 2026 | Aligned the evidence status labels with the series. Attributed the ZAG flame-penetration finding to ZAG and added the localised burn-through recorded in AS-2 and the initial AS-3 run. Linked the three outcomes to the series' protection objectives, added three reporting criteria and an explicit design decision question. Distinguished FM Approved RoofNav assemblies from project-specific FM engineering acceptance. Noted the top-layer scope of the A1 classification and that TPO and bituminous membranes remain open under BROOF(t1). Specified the membrane per ZAG specimen and the renovation-relevant AS-1 and AS-3 build-ups, added ZAG's own distinction between localised burn-through and flame penetration, added the FM ASTM E108 Class A single-layer result and corrected the status of single-layer BROOF(t1) coverage. |
| **1.51** | 21 October 2026 | Aligned the evidence terminology with the two-axis model of What does a fire test actually prove?: claim status (Demonstrated, Physically supported, Contradicted, Unknown) is kept separate from the route to the intended roof (as tested, formally covered, engineering extrapolated). Table 7 now states formal coverage as a route in the Boundary column. |
| 1.52 | 1 November 2026 | Editorial corrections: reframed as a roof-first knowledge synthesis; shortened the author perspective, added method and source limitations, labelled author interpretations and corrected the requested wording and transparency statements. Technical additions and source checks: Checked the primary May 2026 Merkblatt and added the DIN 18234 scope warning. Earlier OFR R01 citations are retained as that edition, not relabelled R02. Full EUMEPS/IVH campaign reports remain unavailable in this revision. |
| 1.53 | 1 November 2026 | Chs. 3 and 10: BROOF method and two-layer Efectis scope clarified (R000982/R000983). Conclusion: fuel-reduction comparison bounded. Method and sources: PR472014 §3.2 and ZAG pp. 3, 46 boundaries added. |
| 1.54 | 1 November 2026 | Ch. 3: BROOF explanation edited as prose with companion reference. Ch. 10 Table 7: single-layer BROOF performance marked UNKNOWN and formal coverage absent, not an adverse test result. ZAG terminology aligned to conclusion p. 46. Authorship and source-boundary structure clarified. |

## THE SERIES

*The roof comes first is a synthesis of knowledge on fire safety and rooftop PV from a roof-first perspective, by Olivier Langejan. Each paper stands on its own; together they follow one line of thought.*

At the time of this version, the series consisted of:

| Paper | For | In one line |
|---|---|---|
| **Rooftop PV on existing commercial buildings** | Asset owners, developers, project teams | A decision framework for resolving roof constraints before the PV investment is committed. |
| **Rooftop PV on new commercial buildings** | Developers, architects, project teams | Designing the roof and PV as one system from the start. |
| **The economics of the rooftop PV decision** | Asset owners, CFOs, risk managers | Probability, consequence and lifecycle cost from the asset owner's perspective, including Business Interruption. |
| **From risk models to design requirements** | Risk engineers, insurers, designers | An application of five established risk frameworks to consequence-limiting design for roofs with PV. |
| **Beyond flame spread (this paper)** | Risk engineers, insurers, fire engineers | How far a rooftop PV fire can travel into the roof before it becomes a building loss, and what a separation layer changes. |
| **What does a fire test actually prove?** | Insurers, risk engineers, specifiers | What a fire test result does and does not demonstrate about a real roof with PV. |
| **DC arcs as a heat source** | Insurers, risk engineers, PV designers | How DC arc faults start, persist and end in rooftop PV. |
| **DC arcs at the roof-PV interface** | Insurers, risk engineers, PV and roof designers | What determines roof exposure to a sustained DC arc and what current evidence shows about measures to limit it. |
| **How much does PV clearance actually solve?** | Insurers, risk engineers, PV designers, asset owners | What module-to-roof clearance does and does not demonstrate about the roof beneath it. |
| **What if the PV panel could not burn?** | Asset owners, risk engineers, insurers, PV designers | What a lower-combustibility PV module does and does not change for the roof beneath it. |
| **What does an inspection actually prove?** | Insurers, risk engineers, asset owners, inspectors | What inspection can establish, what it cannot and what still protects the roof when a fault is missed. |

**All papers and their latest versions: allshield.com/en/olivier-langejan**

Comments, corrections, missing sources, evidence that contradicts a conclusion and field experience are welcome at ol@allshield.com. Relevant input is used in future versions. To be notified of new papers and versions, send a short email to the same address.

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