FIRE SAFETY OF BIO-BASED INSULATION MATERIALS

TECHNICAL REPORT

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EXECUTIVE SUMMARY

Bio-based insulation materials, such as wood fibre, cellulose, hemp or straw, are increasingly used in construction due to their low environmental impact, carbon storage potential and other favourable properties. Their fire behaviour, however, presents specific challenges, particularly related to smouldering combustion.

This white paper supports informed decisions on the fire-safe use of bio-based insulation. It brings together current knowledge, experimental findings and practical mitigation approaches to explain the fire safety challenges, particularly smouldering, and how they can be addressed. It is intended for those developing, specifying, assessing and using these materials, as well as insurers, authorities and fire services. The report highlights both the available evidence and the remaining uncertainties that need to be considered in practice.

Smouldering is a key fire-safety challenge for many bio-based insulation materials. This slow, flameless and often concealed process can persist for extended periods, propagate within cavities and remain undetected after visible flaming has ceased. Experimental studies and documented incidents show that it can contribute to structural degradation, re-ignition and prolonged firefighting operations, with potential consequences for occupants, property and emergency responders.

The report identifies **limitations in current fire classification systems**. European reaction-to-fire methods primarily assess behaviour during relatively short exposures and do not fully capture smouldering or its longer-term effects. EN 16733 assesses a product's propensity to undergo continuous smouldering under specified conditions, but does not establish the smouldering resistance of a complete construction. The assessment gap therefore concerns both materials and construction systems.

Fire performance depends on the complete construction, not on the insulation alone. Protective layers, including gypsum boards and render systems, can delay or prevent ignition and smouldering under relevant exposure conditions. Penetrations, joints and construction defects may compromise this protection, making system integrity, detailing and workmanship critical.

Smouldering also creates **operational challenges**. Insulation can conceal hot spots from thermal imaging, while extinguishment may require extensive opening of building components, prolonged monitoring and repeated intervention. These demands should be explicitly considered in fire-safety strategies.

The report therefore supports a **system-oriented design approach**. Material modification alone cannot currently be relied upon to prevent smouldering across relevant conditions. Measures should address both ignition likelihood and consequence limitation through continuous protective coverings, cavity compartmentation, fire or smouldering barriers, and access for detection and firefighting. Performance-based assessment can support project-specific evaluation beyond prescriptive requirements.

Advances in **testing and modelling** offer opportunities to improve understanding, investigate design parameters and support more targeted fire testing. Their practical application requires further validation and development. Priorities include harmonised smouldering assessment methods, realistic representation of cavities and penetrations, and accessible engineering tools.

Bio-based insulation can be used safely when its specific fire behaviour is addressed within the complete construction system. Combining appropriate material assessment with system-level design and verification is essential to support regulatory compliance and safety while enabling wider adoption of sustainable building materials.

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The reference group comprised stakeholders from Denmark, Sweden and Germany, representing research, fire safety engineering, emergency services, industry and insurance. The views and conclusions presented in this report remain those of the authors and do not necessarily represent the views of the contributing individuals or their organisations.

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ABBREVIATIONS

BR18	Danish Building Regulations 2018	LBO	State building code (Landesbauordnung)
CASPR	Controlled-Atmosphere Smouldering Propagation Reactor	LPG	Liquefied petroleum gas
CO	Carbon monoxide	MBO	Model building code (Musterbauordnung)
CPR	Construction Products Regulation	MDF	Medium density fibreboard
DBI	Danish Institute of Fire and Security Technology	MHolzBauRL	Model timber construction guideline (Muster-Holzbaurichtlinie, Germany)
ETICS	External thermal insulation composite system	OIB	Austrian Institute of Construction Engineering (Österreichisches Institut für Bautechnik)
FIGRA	Fire growth rate index	OSB	Oriented strand board
FRIC	Fire Research and Innovation Centre	PIR	Polyisocyanurate
GKF	Gypsum plasterboard Type F (Gipskarton-Feuerschutzplatte)	PV	Photovoltaic
GK	Building class (Gebäudeklasse)	SBI	Single Burning Item
GWP	Global warming potential	SCBA	Self-contained breathing apparatus
HRR	Heat release rate	THR	Total heat release

SYMBOLS

Symbol	Definition [unit]	Symbol	Definition [unit]
A_b	Burning area [m²]	$\dot{Q}''$	Heat release rate per unit area [kW/m²]
c_p	Specific heat capacity at constant pressure [J/(kg·K)]	t	Time [s]
d	Thickness or diameter [m] or [mm]	V_f	Flame spread velocity [m/s]
k	Thermal conductivity [W/(m·K)]	T	Temperature [K] or [°C]
L_p	Preheating Length [m]	T_{ign}	Ignition temperature [K] or [°C]
m	Mass [kg]	T_∞	Ambient temperature [K] or [°C]
$\dot{Q}$	Heat release rate [kW]	ρ	Density [kg/m³]

GLOSSARY

Term	Explanation
Cavity fire	Fire within a concealed space in a building component, such as a wall, floor or roof. It may involve smouldering, flaming combustion, or both.
Char	Carbon-rich residue formed through pyrolysis or incomplete combustion.
Fire resistance	Ability of a building element to maintain specified functions during fire exposure for a defined period.
Flameout / self-extinguishment	Flameout describes the cessation of flaming; smouldering may continue. To self-extinguish means that combustion ceases without external intervention.
Flammability	Ability of a material or product to undergo flaming combustion under specified conditions.
Heat flux	Rate of heat transfer per unit area, commonly expressed in kW/m² in fire testing.
Performance-based fire safety design	Design approach using engineering analysis and supporting evidence to demonstrate that defined fire-safety objectives and performance criteria are met for relevant fire scenarios.
Pre-accepted solution	Construction or design solution recognised within the applicable regulatory framework as meeting specified requirements when all stated conditions and limitations are satisfied.
Pyrolysis	Chemical decomposition caused by heating. Pyrolysis of bio-based materials can produce gases, vapours and char.
Reaction to fire	A product's response to fire exposure under specified test conditions. Relevant characteristics include ignition, heat release, flame spread, smoke production and flaming droplets. Fire resistance is assessed separately.
Smouldering barrier	Construction detail intended to interrupt smouldering propagation through combustible material.
Smouldering combustion	Combustion without flames, with or without visible glowing. Progressive smouldering is the self-propagating form, sustained by heat released through oxidation.
Smouldering propensity	A product's tendency to develop and sustain smouldering under specified thermal exposure and environmental conditions.
Smouldering resistance	The ability of a building element or system to limit the initiation, persistence and spread of smouldering and maintain its required safety functions during and after thermal exposure.

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1. INTRODUCTION

1.1. Objective, scope, and limitations

Materials such as straw or sawdust have a long history of use as insulation in timber buildings. Growing interest in sustainable construction has renewed attention to materials such as straw, hemp, reed and wood fibre as alternatives to mineral- or petroleum-based insulation. However, questions remain about their fire performance, particularly regarding smouldering. These questions have prompted several targeted research initiatives (see Appendix A – List of Research Projects), but a consolidated overview of national research efforts, regulatory developments and mitigation strategies remains lacking.

This white paper aims to provide a clear, practical overview of the fire safety challenges and potential solutions associated with bio-based insulation in buildings. Within this document, the term *bio-based insulation material* refers to thermal and acoustic insulation products in which the primary insulating constituent is derived from renewable biomass and/or recycled organic materials.

The objectives of this report are to:

- Summarise current knowledge on the fire behaviour of bio-based insulation materials;
- Highlight key risks and challenges, particularly those associated with smouldering;
- Present recent findings from research and testing;
- Support informed decision-making in design, specification and fire strategy development.

The white paper is intended for stakeholders involved in the development, assessment, specification and use of bio-based insulation, including manufacturers, insurers, testing and certification bodies, designers, fire-safety engineers, contractors and authorities. It also addresses fire services by providing background on smouldering and its implications for firefighting and post-fire monitoring.

Particular attention is given to timber constructions incorporating bio-based insulation. However, the discussion is not restricted to timber buildings: the applicability of the findings to other construction types depends on their design, materials and exposure conditions. The geographical focus is on Nordic and German-speaking countries, although the underlying principles have broader relevance. Regulatory requirements must be considered in their national context.

This white paper presents the current state of knowledge drawn from literature, case studies and recent research. It is not intended as a design manual or regulatory guideline. The incidents and experimental studies discussed illustrate possible ignition mechanisms and fire consequences; they do not establish the frequency of such events. Fire safety must also be considered alongside other performance requirements, including heat and moisture transport, emissions and acoustic performance.

Chapter 1 introduces the report's objective and scope. Chapter 2 examines the European fire classification system and regulatory requirements in the selected countries. Chapter 3 explains smouldering combustion, including ignition mechanisms and consequences in building components and the building envelope. Chapter 4 reviews flaming combustion, experimental findings and the transition from smouldering to flaming. Chapter 5 discusses mitigation and design strategies, including ignition prevention, fire spread limitation, firefighting and advanced assessment methods. Chapter 6 summarises the findings and identifies future needs.

1.2. Role of bio-based insulation in the building context

Bio-based insulation materials are increasingly recognised as an important component of low-carbon building design. Compared with conventional mineral- and petroleum-based insulation products, they often exhibit substantially lower embodied greenhouse gas emissions and can contribute to temporary carbon storage within the built environment [1], [2]. Figure 1 illustrates the global warming potential (GWP) of various insulation materials for the product stage (Module A1–A3), expressed in kg CO_2-equivalent per functional unit. A clear distinction can be observed between bio-based and conventional insulation materials. Their potential for reuse, recycling and cascading applications can further support circular economy strategies and extend carbon storage within the built environment.

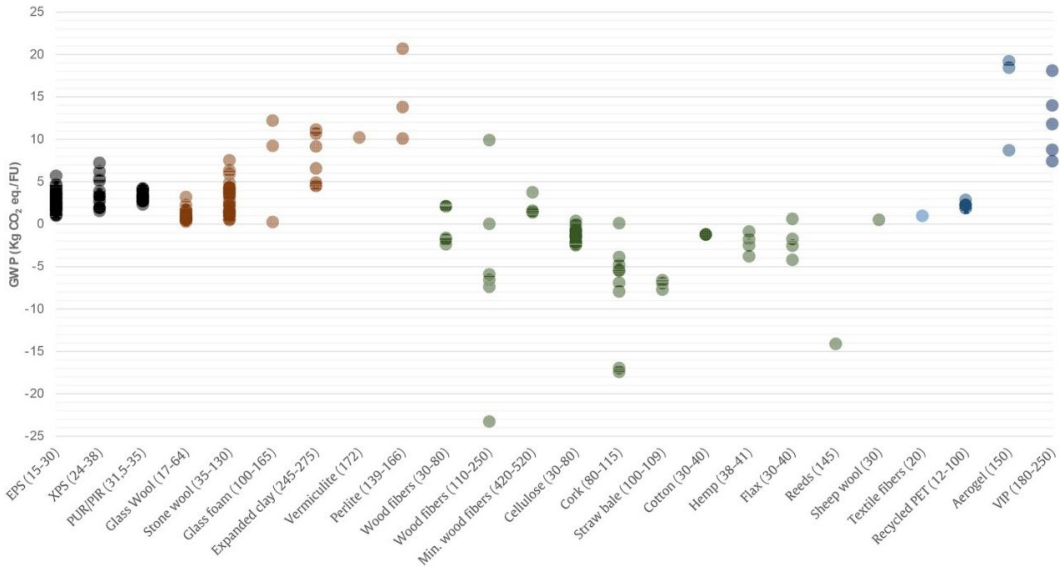


Figure 1: Comparison of the Global Warming Potential (A1-A3) of bio-based insulation and conventional petroleum- and mineral-based insulation materials per functional unit (1 m^2 with R = 1m^2K/W) [3], CC BY 4.0

Product-stage comparisons do not, however, capture the environmental implications of the complete construction, including any additional fire protection measures required for its intended use. In an assessment of multi-storey timber buildings, Steeger [4] found that replacing non-combustible cavity insulation with cellulose or wood fibre offered substantial potential to reduce global warming potential. Additional protective linings, compartmentation or active fire protection systems can, however, offset part of these savings. Importantly, the study also identified combinations of measures that maintained an equivalent assessed fire-safety level while retaining environmental benefits. For the investigated timber-frame building configurations, a fire protection concept incorporating renewable combustible insulation and compensatory construction measures reduced total GWP by approximately 10–11% relative to the study's reference configurations.

In addition to their environmental benefits, many bio-based insulation materials provide favourable thermal and acoustic performance. Their relatively high moisture buffering capacity can help regulate indoor humidity levels and improve indoor comfort [5]. Furthermore, their high specific heat capacity contributes to thermal inertia, thereby reducing indoor temperature fluctuations and improving summer comfort. When properly designed and installed, bio-based insulation systems can achieve service lives comparable to conventional insulation products. The European market for bio-based insulation materials remains relatively small, accounting for approximately 6–7% of the insulation market. Nevertheless, continued growth is anticipated, with revenues projected to exceed €2.3 billion by 2034, driven by climate policies, increasing demand for sustainable construction, and efforts to reduce embodied carbon in buildings [6].

Despite this positive trend, market uptake remains constrained by factors such as higher costs, limited familiarity among practitioners, and regulatory challenges [7]. Among these barriers, fire safety requires particular attention. Many bio-based insulation materials are combustible and susceptible to smouldering, although the consequences depend on their use within the complete construction. Smouldering can persist undetected for extended periods and may lead to delayed fire spread, structural degradation and the release of toxic combustion products. Existing fire testing and classification methods do not always adequately capture these processes under relevant end-use conditions, creating uncertainties for designers, regulators, insurers and end users.

1.3. Raw materials, product types and application fields

Bio-based insulation materials are derived from a diverse range of renewable and recycled feedstocks. Depending on the raw material source and manufacturing process, the resulting products exhibit different physical, thermal, moisture-related, and fire performance characteristics [8]. The dominant material group consists of lignocellulosic fibres, including wood, straw, hemp, flax, and grasses. Wood fibres, typically sourced from softwood residues of the timber industry, are among the most widely used feedstocks due to their availability and well-established processing routes. Agricultural by-products such as straw are increasingly used, either as loose fill or processed into boards, thereby valorising low-cost residues. Other fibres, such as hemp and flax, are cultivated specifically for construction applications.

A second important category comprises recycled bio-based materials, particularly cellulose insulation derived from wastepaper. This approach represents a circular material flow in which post-consumer products are reprocessed into insulation materials. Similarly, recycled jute from used coffee and cocoa sacks or textile fibres is processed into insulation products. Animal-based resources, especially sheep wool, form a niche but technically relevant group. Overall, the raw material portfolio of bio-based insulation is characterised by renewability, potential for regional sourcing, utilisation of by-products and waste streams, biodegradability, and compatibility with circular economy principles.

Bio-based insulation materials are used in a wide range of building applications (see Figure 2), including internal insulation, cavity insulation in walls and floors, and impact sound insulation. In roof construction, they are used for flat-roof insulation as well as for above-, between-, and below-rafter insulation. They are also used in façade systems, such as external thermal insulation composite systems (ETICS) and rear-ventilated façade constructions. Bio-based insulation products are available as loose-fill or blown-in insulation, as well as in batts or rigid board form with varying raw densities. Depending on the intended application, binders, fire-retardant additives or hydrophobic agents are often incorporated.

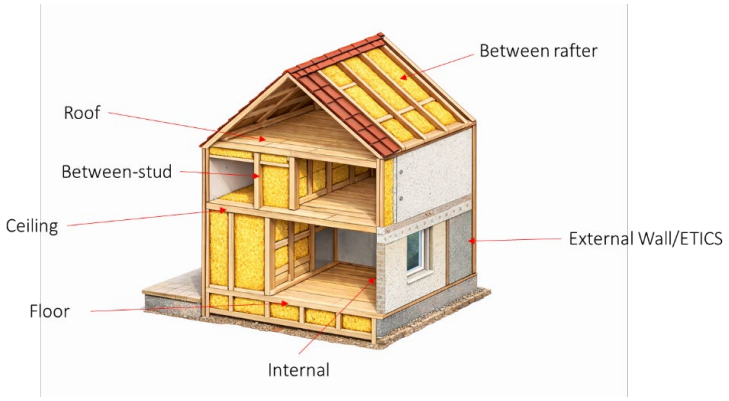


Figure 2: Illustration of application fields for bio-based insulation products as thermal insulation in buildings [AI generated]

2. REGULATORY FRAMEWORK

2.1. European fire classification system

Responsibility for determining the required level of fire safety in construction works lies with the individual countries, through their competent national or regional authorities. Within the European Union, Member States establish these requirements through building regulations, including the performance required of construction products and building elements in specific applications.

The Construction Products Regulation (CPR) provides a harmonised framework for assessing and declaring the performance of construction products and placing them on the EU market. It does not replace national building regulations or establish a uniform fire-safety level for all buildings. European test methods and classifications provide a common basis for expressing performance, which national requirements draw upon.

Annex I of the CPR identifies basic requirements for construction works that guide the development of harmonised technical specifications. These include the following aspects of fire safety [9]:

(a) The load-bearing capacity of the construction works is maintained for a specific period of time to give occupants time to leave the building;
(b) The rescue and emergency services' access is ensured and there are appropriate means to facilitate their work;
(c) The generation and spread of fire and smoke is controlled and limited;
(d) The spread of the fire and smoke to the adjacent construction works is limited;
(e) The safety of rescue and emergency services is taken into consideration.

The European fire classification of construction products and building elements is generally divided into two main categories: reaction-to-fire testing and fire resistance testing. Reaction-to-fire tests assess how a material or product influences fire growth, primarily by measuring its heat release rate during combustion and the amount of smoke generated. These tests typically focus on the early stages of fire development. Fire resistance tests, on the other hand, measure a construction's ability to endure fully developed fire conditions without losing structural stability, load-bearing capacity, or its effectiveness in limiting fire spread and heat transfer through the assembly. For insulation in facades or roofs, additional classification for external fire exposure may be mandatory.

The required test methods and conditions are usually specified in a product standard. The following chapter provides an overview of the European fire classification framework and identifies critical gaps in its ability to account for the smouldering behaviour of bio-based insulation materials.

2.1.1. Reaction-to-fire (EN 13501-1)

Reaction-to-fire classification focuses on the role a material plays in the flaming ignition and growth phases of a fire (see Figure 3). Its purpose is to evaluate how easily a product ignites, how much it contributes to fire spread, and how it affects the production of heat, smoke, and flaming droplets. The main performance indicators include ignition time, heat release rate and total heat release, flame spread, smoke production, and the tendency to generate flaming droplets or particles.

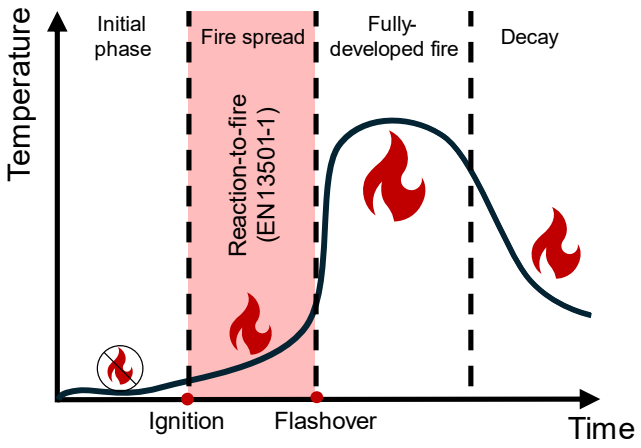


Figure 3: Schematic representation of the fire-growth-phases with focus on reaction-to-fire

In Europe, these properties are assessed according to the harmonised system set out in EN 13501-1 [10]. For wall and ceiling linings, the primary scale is the "Euroclass system", which assigns materials to one of seven main classes, ranging from A1 (best performance) to F (poorest). In addition to the main Euroclass, two supplementary indicators are applied. The first describes smoke production, with classifications from s1 (least smoke) to s3 (most smoke). The second covers flaming droplets or particles, classified from d0 to d2.

An example of this system is the classification A2-s1,d0, which identifies a product with very limited combustibility, producing minimal smoke and no flaming droplets. Mineral fibre insulation often meets this description. In contrast, D-s2,d0 denotes a flammable material that produces higher amounts of smoke and no flaming droplets, such as untreated plywood or medium-density fibreboard.

Determining a product's Euroclass requires a combination of standardised test methods, see Table 1. For test-based classification, A1 requires both the EN ISO 1182 non-combustibility test and the EN ISO 1716 calorific value test. A2 requires either EN ISO 1182 or EN ISO 1716, together with the EN 13823 Single Burning Item (SBI). Classes B, C, and D require the SBI test (Figure 4) in combination with EN ISO 11925-2, the single-flame source test. The lowest classifications, E and F, rely solely on EN ISO 11925-2. Several parameters, based on the listed tests, are used to determine the class. In the Single Burning Item (SBI) test, the most important parameters are FIGRA (Fire Growth Rate index) and THR (Total Heat Release).

Table 1: Reaction-to-fire test methods for construction products according to EN 13501-1

Euroclass	Required Test Methods	Description
A1	EN ISO 1182 (non-combustibility) + EN ISO 1716 (Bomb calorimeter)	No contribution to fire; fully non-combustible materials.
A2	EN ISO 1182 or EN ISO 1716 + EN 13823 (SBI)	Very limited combustibility; minimal contribution to fire.
B, C, D	EN 13823 (SBI) + EN ISO 11925-2	Increasing combustibility from low (B) to moderate (D).
E	EN ISO 11925-2 (single-flame source)	Limited fire performance
F		-

The EN ISO 1182 test measures mass loss and temperature rise of a cylindrical specimen (45 mm in diameter, 50 mm high) inserted into a furnace at 750°C, with visual observation for sustained flaming. EN ISO 1716 uses a bomb calorimeter to measure the gross heat of combustion of a small sample burned in pure oxygen, calculating heat from the temperature rise in the surrounding water. The EN 13823 SBI test evaluates a corner-mounted specimen, 1.5 m high with two wings of 1.0 m and 0.495 m, exposed to a 30 kW gas burner (see Figure 4). It measures heat release rate, flame spread, smoke production, and flaming droplet formation.

The EN ISO 11925-2 test applies a small gas flame, 20 mm high, at a 45° angle to the specimen's surface, recording ignition, flame spread, and the production of flaming droplets capable of igniting a filter paper placed below the sample.



Figure 4: A Single Burning Item test with wood panels

2.1.2. Fire resistance (EN 13501-2)

Fire resistance classification evaluates a construction element's ability to maintain its performance under severe thermal conditions analogous to a fully developed (post-flashover) fire. Unlike reaction-to-fire tests, which focus on the early growth stages and material-level behaviour, fire resistance testing examines entire building elements (e.g. walls, floors, ceilings, doors) under standardised fire conditions to determine whether they can continue to contain the fire (compartmentalisation) and maintain structural integrity.

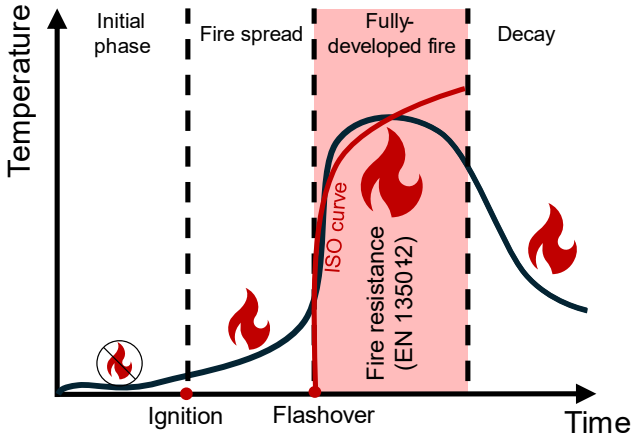


Figure 5: Schematic representation of the fire-growth-phases with focus on fire resistance

Fire resistance is tested in accordance with EN 1363, which specifies exposure of the specimen to the ISO 834 fire curve. This curve describes the furnace temperature as a logarithmic function. The test specimen can be oriented vertically or horizontally, depending on the type of element, and the furnace can be fuelled by gas or oil. When separating elements or partitions (e.g. walls or floors) are tested, they are exposed from one side, replicating a compartment fire exposure scenario.

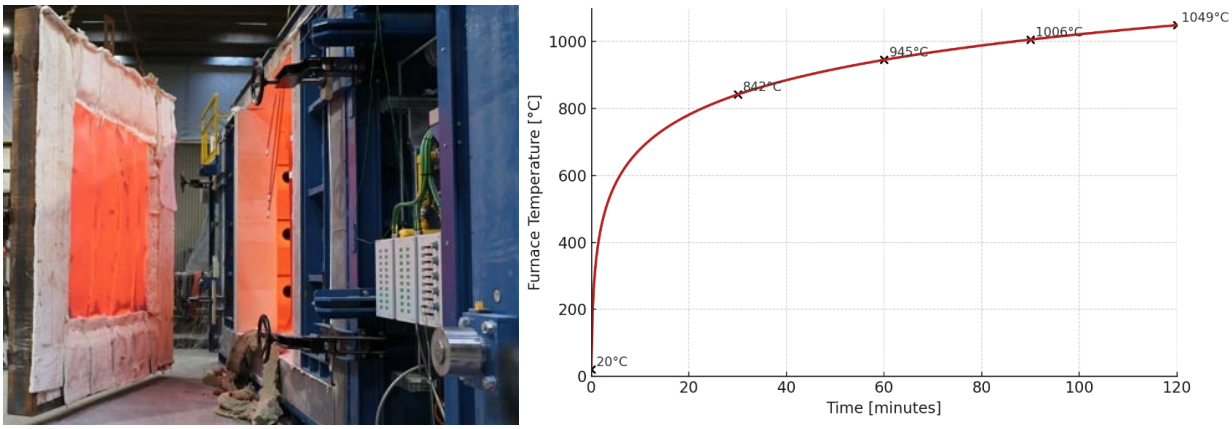


Figure 6: DBI's multi-furnace (left) and ISO 834 standard fire curve (right)

For separating elements (e.g. walls, floors, doors) classification is based on the time to failure for one or more specified performance criteria:

- Load-bearing capacity (R) measures the ability of load-bearing elements to support their design load during standard fire exposure.
- Integrity (E) is the ability to prevent the passage of flames or hot gases that could ignite materials on the unexposed side.
- Insulation (I) refers to limiting heat transfer through the element, with a maximum permitted average temperature rise of 140°C and a localised rise of 180°C on the unexposed surface.

Additional classifications include radiation control (W), mechanical impact resistance (M), self-closing (C), smoke leakage (S), and soot fire resistance (G). For covering products, fire protection ability (K) describes the capacity of a wall or ceiling covering to protect materials behind it against ignition, charring and other thermal damage for a defined period. Testing is conducted in accordance with EN 14135, while classification is governed by EN 13501-2. The test exposes the covering to the standard temperature-time curve specified in EN 1363-1, corresponding to ISO 834, and evaluates temperatures at specified locations behind the covering. Figure 7 illustrates the differences between the assessment of fire protection ability (K) and the thermal insulation criterion (I) used in fire-resistance testing of building elements. EN 13501-2:2023 distinguishes two categories of fire protection ability: K_1, classified for 10 minutes, and K_2, classified for 10, 30 or 60 minutes. The distinction concerns both the damage criteria and the substrates covered by the classification.

Whereas the previous test standard combined temperature measurements with post-test visual inspection, EN 14135:2025 additionally permits a temperature-only evaluation. Under this option, the covering must not collapse, and the temperature rise at any measuring location must not exceed 270 K, or 75 K when using the specified thermoplastic substrate (EPS or XPS). A combined temperature and visual evaluation remains available for particleboard substrates. Within each evaluation option, the test standard specifies identical performance criteria for coverings designated K_1 and K_2.

The field of direct application depends on the tested substrate. Testing with the specified thermoplastic substrate permits application to any substrate, whereas testing with particleboard permits application to substrates with a density of at least 300 kg/m³. For low-density substrates, the results apply to substrates of the same material type with density and moisture content equal to or greater than those tested. Tests using a special substrate apply only to that substrate. These extensions remain subject to the other direct-application rules, including those concerning fixings, air gaps and orientation.

However, the performance criteria and substrate-extension rules in EN 14135:2025 are not fully aligned with the K_1 and K_2 classification provisions in EN 13501-2:2023. Consequently, meeting the revised test standard's criteria does not, by itself, demonstrate compliance with the classification standard due to the discrepancy between the two. Until the revision of EN 13501-2:2023 is in place, testing the K-criteria is subject to national assessments.

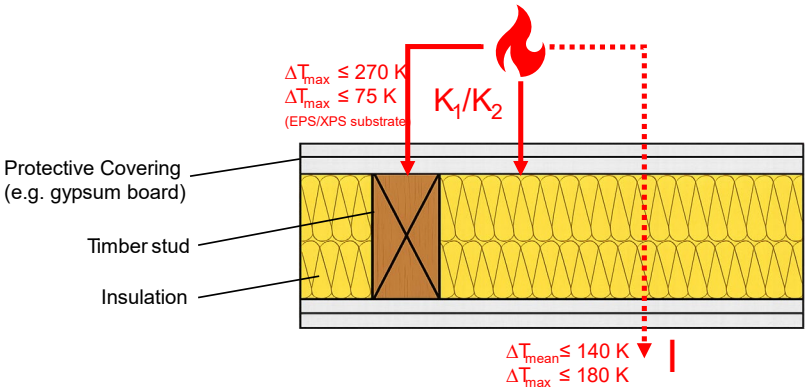


Figure 7: Visualisation of the principal differences between fire protection ability (K-) and insulation (I-)criteria

2.1.3. External fire exposure

The classification system also extends to external fire spread and roof coverings. For façades, compliance is typically achieved by meeting reaction-to-fire requirements for materials set by prescriptive (also called pre-accepted) regulations. However, some national regulations also require large-scale façade system fire tests (such as SP FIRE 105, BS 8414 or ISO 13785). These tests evaluate complete wall assemblies under fire conditions that aim to represent specific external fire scenarios.

Reaction-to-fire tests assess a product's contribution to fire development under specified exposure and mounting conditions. Large-scale façade tests instead assess the behaviour of the assembled system, including interactions between the cladding, insulation, cavities, fixings and fire barriers. These construction details can influence fire spread across the façade and within concealed spaces, so the reaction-to-fire classification of individual products alone does not establish the performance of the complete façade system. Depending on the test method and applicable assessment criteria, performance is evaluated using the damaged area of the façade after the test, temperature measurements near the façade and within the façade elements, heat flux meter readings, and observations of falling and/or burning construction components.

The impact of external fire exposure on roofs is classified in accordance with EN 13501-5, using four test methods specified in CEN/TS 1187. The classification ranges from B_{ROOF} (Highest performance) to F_{ROOF} (no performance determined). The suffix (t1) to (t4) denotes the applied test method, reflecting different fire exposure scenarios (e.g. with/without wind and radiant heat).

2.1.4. Smouldering

EN 16733 is the European Standard specifically dedicated to determining the propensity of building products to undergo continuous smouldering when exposed to an open flame under natural convective airflow. The smouldering test stand consists of a rectangular test specimen measuring 800 mm x 300 mm and a maximum thickness of 100 mm, mounted vertically on a frame (see Figure 8). For loose-fill insulation, a wire-mesh box is used. Six type K thermocouples are inserted from the back into the centre at intervals of 100 mm within the vertical specimen.

The test begins with a 15-minute flame impingement from a Teclu burner, positioned at the lower end of the specimen. After the burner is removed, flames may be extinguished by applying a calcium-silicate board. The test ends when all thermocouples indicate temperatures below 50 °C that have remained stable or decreased for at least 60 minutes, or when the maximum test duration of six hours is reached. It may be terminated earlier once continuous smouldering has been established.

A product is considered prone to continuous smouldering if any of the following occurs: sustained flaming at the top or either vertical side without visible surface flame spread; re-ignition on any surface or edge at least five minutes after burner removal and after sustained surface flaming has ceased; a temperature rise exceeding 250 K above the initial temperature at the top thermocouple after burner removal; or, at the six-hour endpoint, a temperature above 50 °C at any thermocouple or a temperature increase during the final 60 minutes.

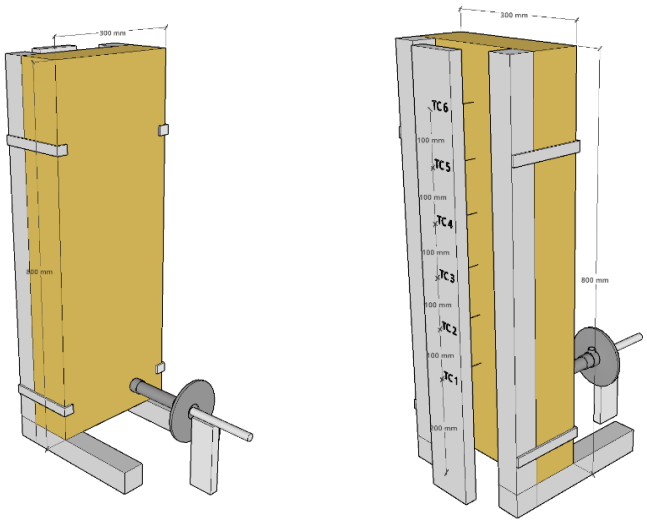


Figure 8: Schematic visualisation of the EN 16733 smouldering test rig (front and back side)

With respect to external fire exposure, the new European façade testing framework [11] incorporates an optional smouldering assessment procedure. Nevertheless, no harmonised classification methodology has been established yet. Moreover, proposals to extend the testing duration from 60 minutes to 6 hours (EN 16733) or 15 hours (DIN 4102-20) pose challenges for implementation, standardisation, and reproducibility.

Other standardised methods address smouldering in thermal insulation at national or regional level. These include the Nordic method NT FIRE 035 for the flammability and smouldering resistance of loose-fill insulation, the British standard BS 5803-4, and North American methods such as ASTM C739 and CAN/ULC-S129. The FRIC report provides an overview of their test principles, assessment criteria and limitations [12].

2.1.5. Discussion

European fire tests and classifications provide a common basis for assessing and expressing performance, while national and regional building regulations determine the required safety levels and the conditions under which products and construction systems may be used. The central question for bio-based insulation is therefore whether the available performance information adequately addresses the fire-safety requirements of its intended application.

Where national building regulations restrict the use of combustible materials, any consideration of alternative solutions should be supported by evidence that the required safety levels are maintained. For bio-based insulation, this raises the question of whether existing test methods and classifications adequately represent the relevant fire behaviour and construction conditions [13], [14]. The aim is not to lower safety requirements, but to ensure that assessment methods provide sufficient information to evaluate the intended application, including potential smouldering within the construction.

Reaction-to-fire tests, including the Single Burning Item (SBI) test, provide information on a product's contribution to fire development under specified exposure and mounting conditions. The resulting classification describes performance within the conditions covered by the assessment. It should therefore be interpreted together with the tested configuration and the classification's field of application. For insulation products, a distinction is needed between the performance of the insulation itself and that of the complete construction in which it is installed. Mounting arrangements, substrates and protective coverings can influence the measured performance [15]. Loose-fill products require defined containment arrangements during testing, while insulation in buildings may be enclosed within cavities or protected by linings. These differences do not invalidate product-level testing, but they limit the conclusions that can be drawn about configurations outside the assessment's field of application. The relevant question is whether the available classification and supporting evidence adequately address the intended use and the applicable national fire-safety requirements.

Reaction-to-fire and fire-resistance assessments address different aspects of fire performance. Reaction-to-fire classification describes a product's contribution to fire development under specified test conditions. Fire-resistance classification describes the ability of a building element to maintain the applicable functions, such as load-bearing capacity, integrity and thermal insulation, for a specified period under standardised fire exposure. For constructions containing combustible insulation, an additional question is whether smouldering can develop, persist or propagate after visible flaming has ceased, and whether this can compromise the required performance of the construction (see Figure 9). Where this behaviour is relevant to the intended application, it needs to be addressed in the supporting fire-safety assessment.

The assessment of smouldering should extend beyond determining whether an individual insulation product can undergo continuous smouldering. EN 16733 addresses a product's propensity to undergo continuous smouldering under specified test conditions. This provides useful information about the product, but does not by itself establish the behaviour or safety of the construction in which it is installed.

For this discussion, a distinction is therefore made between propensity to smoulder and smouldering resistance. Propensity to smoulder describes a product's tendency to develop and sustain smouldering under specified exposure and environmental conditions. Smouldering resistance is used here as a construction-level concept: the ability of a building element or system to limit the initiation, persistence and spread of smouldering, and to maintain its required safety functions during and after thermal exposure.

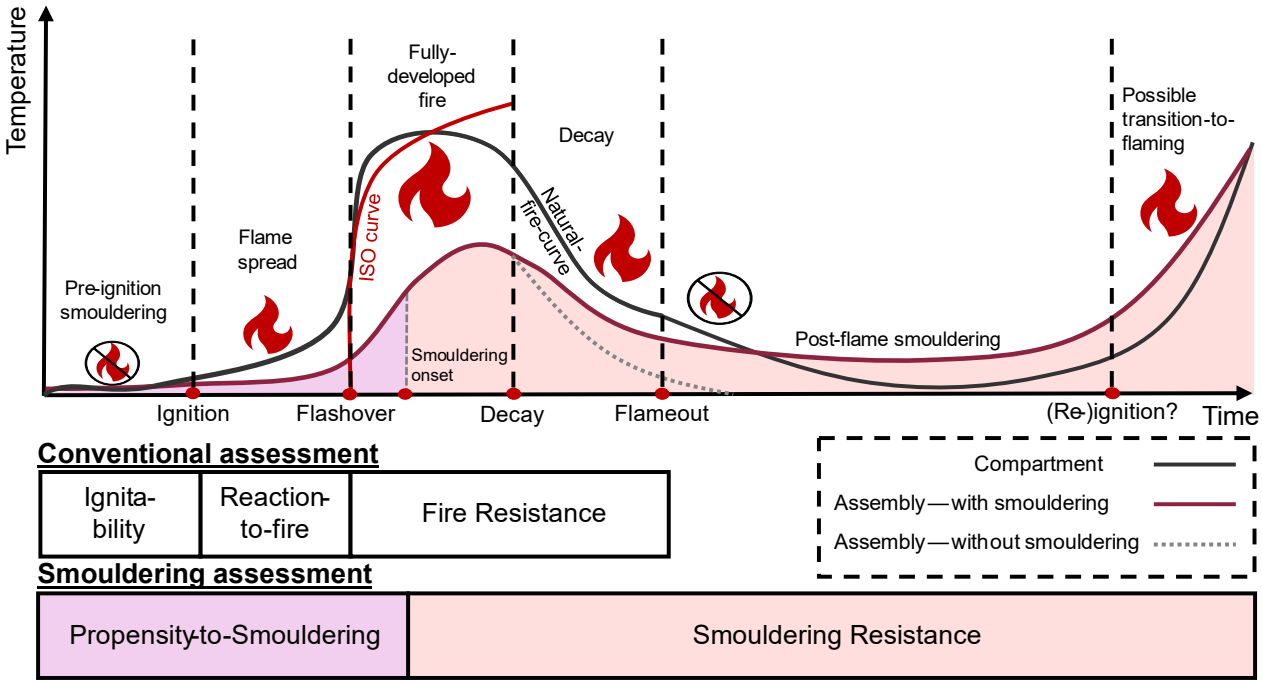


Figure 9: Conceptual illustration of fire development vs. conventional assessment and potential future pathways for smouldering assessment, distinguished by the building product propensity to smouldering and the smouldering resistance of building assemblies

Smouldering resistance consequently depends on more than the insulation material alone. Relevant factors include protective coverings, joints and penetrations, cavity geometry, oxygen availability, heat transfer and interactions with adjacent materials. The assessment should consider both the possibility of concealed smouldering and its consequences, including continued smoke production, loss of structural or separating performance, and possible transition to flaming. The observation period should be sufficient to capture delayed behaviour after external heating or visible flaming has ceased.

Figure 9 illustrates this broader assessment perspective. The distinction concerns the level and purpose of assessment, rather than two separate chronological phases: product propensity remains relevant throughout the event, while construction-level resistance includes prevention of smouldering as well as limitation of its subsequent development. Here, “smouldering resistance” is a proposed assessment concept, not a designation of a harmonised European classification.

The current assessment framework for insulation products primarily focuses on flammability, while smouldering is not adequately addressed. Its assessment should not be reduced to a material’s propensity to smoulder, but should also consider the (smouldering) resistance of the complete construction

Ultimately, a fundamental limitation in the current evaluation of insulation materials lies in the strong focus on material-level performance, particularly reaction-to-fire properties, rather than on the fire behaviour of the complete building system. In addition, regulatory assessments predominantly address flaming combustion, while smouldering phenomena receive comparatively little attention. Applying requirements derived from test methods that are not well aligned with the specific behaviour of bio-based insulation materials may lead to unsafe outcomes in some cases, and in others may unnecessarily restrict the broader adoption of sustainable construction solutions.

2.2. Prescriptive requirements across countries

The following section provides a simplified comparative overview of prescriptive fire safety requirements for standard buildings in selected European countries. The overview focuses primarily on reaction-to-fire requirements for materials and exposed surfaces, with particular attention to their implications for timber constructions incorporating combustible bio-based insulation. The regulatory overview reflects the provisions and guidance reviewed as of August 2026. Subsequent amendments and transitional arrangements should be checked against the applicable national sources.

The intention is to illustrate typical minimum requirements for pre-accepted solutions in conventional buildings with standard occupancy. It does not represent a complete or legally binding interpretation of the respective national building regulations. Requirements for exposed surfaces should be distinguished from those applying to insulation concealed within a construction. A requirement for an exposed lining does not automatically apply to the insulation behind it, nor does the lining's classification alone establish the fire performance of the complete assembly. The applicable requirements must therefore be considered in relation to the insulation's position, protective coverings and intended construction.

Fire safety regulations are complex, and requirements depend on numerous factors, including building height, building class, occupancy type, fire load, the presence of active fire protection systems, and proximity to other buildings. National and regional regulations may contain additional requirements, exemptions, transitional provisions, or references to system tests and approvals that are not fully captured in this overview.

Furthermore, many countries allow deviations from prescriptive provisions through performance-based design if compliance with the functional fire safety objectives can be demonstrated. In practice, approvals may depend on the interpretation of authority, national annexes, technical approvals, or project-specific documentation. For any specific project, the applicable national building code, technical guidelines, and approval procedures must be consulted, and competent fire safety professionals must verify compliance.

Compliance with minimum regulatory requirements should not be interpreted as a guarantee that a building will remain repairable or usable after a fire. Project-specific objectives for property protection and business continuity may require additional measures.

2.2.1. Denmark

The building code requirements related to fire safety in Denmark are governed by the *Bygningsreglementet* (BR18) chapter 5 - Fire. According to the building code, any material with a raw density of less than 300 kg/m³ is generally considered an insulation material. A separate classification regarding the smouldering behaviour of insulation materials is not currently in place.

Under the prescriptive solutions in BR18, insulation products are generally required to meet at least Euroclass D-s2,d2. Insulation products with lower classifications may be permitted, provided additional conditions are met. These typically include cavity-free installation and full protection by coverings classified at least $K_1$10 / B-s1,d0, or incorporation behind building elements providing at least EI 30 fire resistance, depending on building height and configuration.

Where the top-storey floor is above 5.1 m, insulation products with a lower reaction-to-fire classification than B-s1,d0 may only be used if the load-bearing structure is non-combustible (at least A2-s1,d0). Consequently,

combustible load-bearing structures such as timber frames above 5.1 m require insulation products that meet at least B-s1,d0 within the prescriptive framework.

The Danish pre-accepted solutions also permit combustible load-bearing structures in buildings with the floor of the uppermost storey up to 12 m above ground, subject to specified conditions. Insulation used in connection with combustible load-bearing elements must, under these solutions, achieve at least reaction-to-fire class B-s1,d0.

In addition to material classification requirements, concealed cavities must be interrupted by fire stops at boundaries between fire compartments to prevent fire and smoke from bypassing fire-separating building elements. This includes junctions between internal fire-separating elements and external walls. The above restrictions concern pre-accepted solutions. Alternative designs may be possible through performance-based fire-safety design, subject to the applicable documentation and approval requirements.

2.2.2. Sweden

In Sweden, fire safety in buildings is regulated by the Plan- och bygglagen (PBL – Planning and Building Act) and the associated Plan- och byggförordningen (PBF – Planning and Building Ordinance). These are further specified in Boverket's mandatory provisions and general recommendations on fire safety for buildings. A dedicated classification or regulatory framework addressing the smouldering behaviour of insulation materials is currently not included in the Swedish building regulations.

Building classes (Byggnadsklasser) are determined based on building height, number of storeys, and intended use. Byggnadsklass 0 applies to buildings with particularly high complexity or risk, requiring performance-based design. Byggnadsklass 1 generally includes multi-storey buildings with higher safety requirements, while Byggnadsklass 2 and Byggnadsklass 3 cover buildings with progressively lower requirements, typically including smaller multi-storey and low-rise buildings, respectively.

For interior surfaces in Byggnadsklass 1 buildings, ceiling surfaces are generally required to achieve at least class B-s1,d0 when attached to non-combustible substrates or protected by fire-protective cladding, while wall surfaces are generally required to achieve at least class C-s2,d0. In Byggnadsklass 2 buildings, interior ceiling surfaces are generally required to achieve at least class C-s2,d0 when attached to non-combustible substrates or ignition-protective cladding. No additional specific requirements are generally imposed on wall surface finishes beyond the general requirements. In Byggnadsklass 3 buildings, no specific requirements for interior surface finishes are generally imposed beyond the basic requirements. However, stricter requirements may apply depending on the occupancy class (verksamhetsklass).

For façades and external walls, the required fire performance also depends on the building class. In Byggnadsklass 2 and Byggnadsklass 3 buildings, exterior wall surfaces are generally required to meet at least class D-s2,d2. For Byggnadsklass 1 buildings, façade systems must either consist of non-combustible materials (typically A2-s1,d0 or better) or be verified through large-scale system testing in accordance with SP FIRE 105. This façade test is a full-scale system test that includes both the external cladding and underlying insulation. Any modification of the tested assembly (e.g. substitution of insulation or façade materials) requires a new test to maintain validity of the classification.

Combustible insulation may also contribute to the permanent fire load considered when determining fire-safety requirements, including when applying prescriptive provisions. Under the Swedish rules, its treatment

depends on whether it is protected against involvement throughout the complete fire, including the cooling phase, and whether the conditions for using a standard allowance for permanent fire load are met.

As a general principle, combustible materials may be used in all building classes, provided that the required surface fire performance is achieved through appropriate protective linings or coverings. In addition, the spread of fire between compartments must be limited, for example by interrupting the insulation. The requirements differ depending on building class and building element. Consequently, combustible insulation materials (e.g. Euroclass E or F) may be used if they are sufficiently protected during the initial phase of a fire by appropriate coverings or assemblies. This regulatory approach enables a comparatively broad use of insulation materials from renewable raw materials within the Swedish prescriptive framework.

2.2.3. Norway

According to Byggteknisk Forskrift TEK17, Section 11-9, the use of combustible insulation (that does not meet the minimum class A2-s1,d0) is permitted, provided that the building component meets the fire resistance requirements and the insulation does not have unacceptable contributions to the development of fire. This can be done by protection with covering. In addition, the spread of fire between compartments must be limited, for example by interrupting the insulation.

The applicability depends on the building's risk and fire class. Prescriptively, combustible insulation materials based on cellulose or textile fibres and similar materials may be used as cavity insulation in buildings of Fire Class 1 with up to 3 stories. The insulation must comply with Euroclass E or be classified in accordance with NT Fire 035.

Interior surfaces on walls and ceilings must have a minimum rating of Class D-s2,d0. Also, combustible insulation must be covered with covering with a minimum $K_2$10 / D-s2,d0, depending on fire class and size of the fire cell (smaller or larger than 200 m2). In Fire Class 1 with up to 3 stories, the insulation may be uncovered in cold, unfurnished attics and pitched roofs.

For exterior wall coverings of single-family homes, the requirement D-s3,d0 applies, and for taller buildings, the general requirement is B-s3,d0. In addition, materials in the cavity behind the covering, e.g., a wind barrier, must have at least the same classification as the external covering. For buildings in fire class 1 and for dwellings up to 3 stories, the materials in the cavity can be unclassified. Combustible insulation as external insulation, e.g. ETICS, must be verified as a complete system using the SP FIRE 105 façade test. This does not apply for fire class 3 and risk class 6. In general, it is accepted to use performance-based design to deviate from the prescriptive rules.

2.2.4. Finland

The fire safety in buildings is regulated by 848/2017 Decree of the Ministry of the Environment. Buildings are divided into four fire classes:

- P0: Design based mainly or entirely on a design fire scenario.
- P1: Standard class with the strictest requirements for fire resistance and materials.
- P2: Intermediate class with moderate requirements
- P3: Lowest class with the least stringent requirements.

Load-bearing structures in P1 and P2 fire class buildings with one or two storeys generally require at least D-s2,d2 materials. In P2 class loadbearing structures can be combustible (D-s2,d0) and it can be built up to 28m. Insulation in P2 buildings with more than two stories must be A2-s1,d0. No fire resistance requirements are prescribed for roof structures of an attic or void that are not essential load-bearing structures of the building's structural body or structures that brace the structural body in a fire.

The external wall in P1 buildings must mainly consist of materials of at least class A2-s1,d0. In P2 buildings of more than two storeys and in P1 buildings higher than 56 metres, thermal insulation and other fillings must also meet class A2-s1,d0. In P1 buildings not exceeding 56 metres, thermal insulation products of class B-s1,d0 may be used, or lower-class products if they are protected and positioned so that fire spread into the insulation is delayed for at least half of the required fire resistance time of the adjacent separating elements. If the insulation does not meet class D-s2,d2, it must be interrupted with fire partitions at every two storeys up to a height of 28 metres, and at every storey above that. Alternatively, for P1 buildings up to 56 metres in height, the fire performance of the external wall may be demonstrated through a full-scale test.

2.2.5. Germany

The federal building codes "Landesbauordnungen (LBO)" regulate the prescriptive building requirements in Germany, which are based on a model building code "Musterbauordnung (MBO)". The requirements are specified by each state by technical building regulations, particularly by the "Verwaltungsvorschrift Technische Baubestimmungen – VV-TB". This refers to technical standards and special regulations, e.g., for high-rise buildings, schools, or industrial buildings.

In most federal building codes, bio-based insulation materials with a fire classification of at least E are permitted for use in standard buildings with a maximum upper floor height of 7 meters. However, exceptions apply to exterior walls classified as EI 30 and to elements without prescribed fire-resistance requirements, such as certain roofs and non-load-bearing, non-separating walls.

Since 2020, a new directive on fire protection requirements for building components and exterior wall covering in timber construction, the "Muster-Holzbaurichtlinie (MHolzBauRL) 2020," has been introduced and incorporated into the technical building regulations. A new version, particularly with further facilitations for solid wood construction, was released in 2024. Nevertheless, combustible insulating materials, e.g., in load-bearing exterior walls, are still not permitted. The only exception to this is in the federal state of Baden-Württemberg, where combustible insulation is permitted for buildings with an uppermost-storey floor height of up to 13 m.

According to MBO, insulation materials in external thermal insulation composite systems (ETICS) for façades must be classified as combustible material with limited contribution to fire according to DIN 4102-1, respectively, at least C-s2,d0 to DIN EN 13501-1 with additional requirements on the smouldering behaviour. This means that the insulation materials must not be prone to smouldering.

The European test standard DIN EN 16733 provides an opportunity to classify the smouldering behaviour and the DIN 4102-20 test is used to assess façade systems. Since there is no technical standard for bio-based ETICS, a general construction technique permit is mandatory for each system. There is currently no general approved system utilising bio-based insulation materials that fulfils all requirements for use in multi-story buildings. In conjunction with external timber wall covering, the MHolzBauRL requires non-combustible facade insulation materials.

2.2.6. Austria

In Austria, building regulations are governed at the federal state (Bundesländer) level. However, efforts have been made to harmonise these regulations through the guidelines of the Austrian Institute of Construction Engineering (OIB). Fire performance requirements for construction products are primarily defined by building classes (Gebäudeklassen, GK) and are specified in OIB Guideline 2, particularly in Table 1a. The classification system for reaction to fire is based on EN 13501-1.

In practice, the use of insulation materials made from renewable raw materials is generally limited to building classes GK 1 to GK 3 (i.e. buildings with up to three storeys) within the prescriptive framework. For roof constructions in these building classes, insulation materials may achieve lower reaction-to-fire classifications (e.g. class E) provided that the roof covering meets the classification $B_{ROOF}(t1)$, ensuring adequate protection against external fire exposure.

For buildings in classes GK 4 and GK 5, stricter requirements apply. In these cases, insulation materials used in roof constructions are generally required to achieve at least class B according to EN 13501-1.

Deviations from these prescriptive requirements are possible within the Austrian regulatory framework, provided that equivalence with the technical requirements is demonstrated, typically through a performance-based (engineering) fire safety design.

2.2.7. Switzerland

In Switzerland, building regulations vary from canton to canton. Due to the country's federal system, each canton has its own legislation. However, the prescriptive fire safety requirements are primarily derived from the VKF regulations (*Vereinigung Kantonaler Feuerversicherungen* – Association of Cantonal Fire Insurers), which are applied nationwide. These VKF fire protection provisions consist of the VKF Fire Protection Standard and the VKF Fire Protection Guidelines. Material classification is based primarily on the European standard EN 13501-1. Building materials are then assigned to the following fire behaviour groups:

- RF1 – No contribution to fire
- RF2 – Low contribution to fire
- RF3 – Acceptable contribution to fire
- RF4 – Unacceptable contribution to fire

Materials labeled with "cr" (critical behaviour) are those that may cause unacceptable fire effects due to excessive smoke production, dripping or falling while burning, corrosivity, or similar hazards. E.g., materials classified as E under EN 13501 are rated RF3-cr. Fire performance requirements for materials are determined mainly by the total building height, which is categorized in Low-rise buildings (≤ 11 m), Medium-rise buildings (≤ 30 m) and High-rise buildings (> 30 m).

The following rules apply to standard buildings: According to VKF Fire Protection Guideline 14-15, Table 4.2, RF 3 materials (minimum class D-s2,d1) are required for insulation layers in walls and ceilings of low-rise buildings. Medium-rise buildings must use RF 2 materials (minimum class C-s2,d1), while high-rise buildings require RF 1 materials. In high-rise buildings, RF 2 is permitted only if an automatic fire suppression system is installed. Exceptions apply to components that do not have fire-resistance requirements. Along escape routes, stricter rules are in place: insulation materials must generally be non-combustible. Depending on the layering,

combustible insulation with RF3-cr (E under EN 13501) is in most cases allowed for roofs in low- and medium-rise buildings.

According to VKF Fire Protection Guideline 14-15, Table 3.2.8, Insulation that is classified as RF3-cr or better (E under EN 13501) may be used in exterior wall covering systems of low-rise and medium-rise buildings. In medium-rise buildings, RF2-cr or better is required. Wooden facades (RF3) are possible if the rules of a “Stand der Technik Papier”, Lignum Dokumentation are considered. In high-rise buildings, only non-combustible insulation (RF1=A2-s1,d0 or better) is allowed. External thermal insulation composite systems of medium-height buildings whose insulating materials consist of combustible materials must be designed with a construction recognized by the VKF or equivalent or have a circumferential fire barrier made of RF1 building materials (melting temperature ≥ 1,000 °C) with a minimum height of 0.2 m on each floor. Requirements applicable to façade cladding and the construction as a whole must also be considered for the intended application.

In practice, there are virtually no fully 'performance-based' approaches; the standard specifications are always partially used. Additional regulations (e.g. those relating to smoke extraction) detail the extent to which the standard specifications apply and when proof of performance is required.

2.2.8. Comparison of prescriptive requirements for combustible insulation in timber buildings

The comparison illustrates noticeable differences in how selected Northern European and German-speaking countries regulate the prescriptive use of combustible insulation materials in combustible structures (e.g. timber buildings). While all countries operate within the Euroclass framework, the level of regulatory acceptance varies considerably depending on building height and façade configuration. Importantly, the table reflects prescriptive pathways under standard conditions (no sprinklers, standard occupancy). In practice, many jurisdictions allow performance-based approaches that can modify or relax these limitations when equivalent or sufficient fire safety can be demonstrated.

For low-rise buildings with typically fewer than three storeys, most countries allow the use of combustible insulation materials under prescriptive provisions, particularly when installed within protected cavities. Germany and Austria show relatively broad acceptance for façade systems and cavity insulation in this building category, although certain configurations may still require minimum performance levels. Switzerland and Norway generally permit combustible insulation in low-rise buildings, but impose specific restrictions based on construction type and detailing. Denmark and Sweden also allow combustible insulation in low-rise applications, though protective measures or minimum classifications are typically required. Overall, low-rise timber buildings represent the regulatory environment with the highest level of prescriptive acceptance for bio-based insulation materials across all countries considered. In contrast, multi-storey timber buildings reveal significantly greater divergence between national approaches.

Germany and Austria adopt comparatively restrictive prescriptive positions, particularly for façade systems and cavity insulation in taller buildings. In these contexts, non-combustible solutions or high-performance classifications are frequently required, effectively limiting the prescriptive use of combustible insulation. Switzerland occupies an intermediate position: combustible insulation remains possible in certain assemblies but is subject to tighter restrictions and may require additional protective measures or system-based validation.

Country	Low-rise* timber buildings		Multi-storey timber buildings	
	External wall insulation	Insulation within construction cavities	External wall insulation	Insulation within construction cavities
Germany				
Austria				
Switzerland				
Sweden				
Denmark				
Norway				
Finland				
* typically 1-3 storeys				

Color	Meaning
	Generally outside the scope of prescriptive solutions
	Strongly restricted (e.g. Class C or higher or additional testing required)
	Partly restricted (e.g. Minimum class D)
	Generally accepted

Figure 10: Simplified comparison of prescriptive restrictions on combustible insulation in timber buildings, primarily reflecting reaction-to-fire requirements. Assumes standard occupancy, no special risks and no sprinklers unless required by regulation. Colours indicate general tendencies, not product or system approval; country-specific conditions apply. Alternative performance-based solutions are not shown.

Denmark and Norway demonstrate moderate restrictions in multi-storey buildings. Combustible insulation may still be feasible, but it typically requires higher classifications, additional compartmentation measures, or verification of the façade system. Sweden stands out for maintaining a comparatively broad prescriptive acceptance of combustible insulation in cavity applications, even in multi-storey timber buildings, provided appropriate protective linings are used. However, façade systems in taller buildings are generally subject to stringent requirements or system testing.

Ultimately, the comparison shows that while combustible and bio-based insulation materials are widely accepted in low-rise timber construction across Northern and Central Europe, their prescriptive use in multi-storey buildings remains more constrained and highly dependent on national regulatory philosophies.

3. SMOULDERING COMBUSTION

3.1. Introduction

This chapter introduces the fundamental principles of smouldering combustion, examines ignition scenarios in building components and the building envelope, and discusses the consequences of sustained smouldering for fire spread and structural safety. A more comprehensive discussion of the underlying theory can be found in [16], [17], [18], [19], [20].

Smouldering is defined as *combustion of a material without flame formation, with or without visible light, and encompasses glowing* [21]. Smouldering and flaming are distinct forms of combustion. Their main difference lies in where oxidation (the reaction of fuel with oxygen) takes place. In flaming combustion, this reaction occurs mainly in gases released from the material. In smouldering, it occurs at the surfaces of the solid material or its char. Figure 11 compares the two processes, highlighting differences in heat generation, oxygen supply and the location of the reactions.

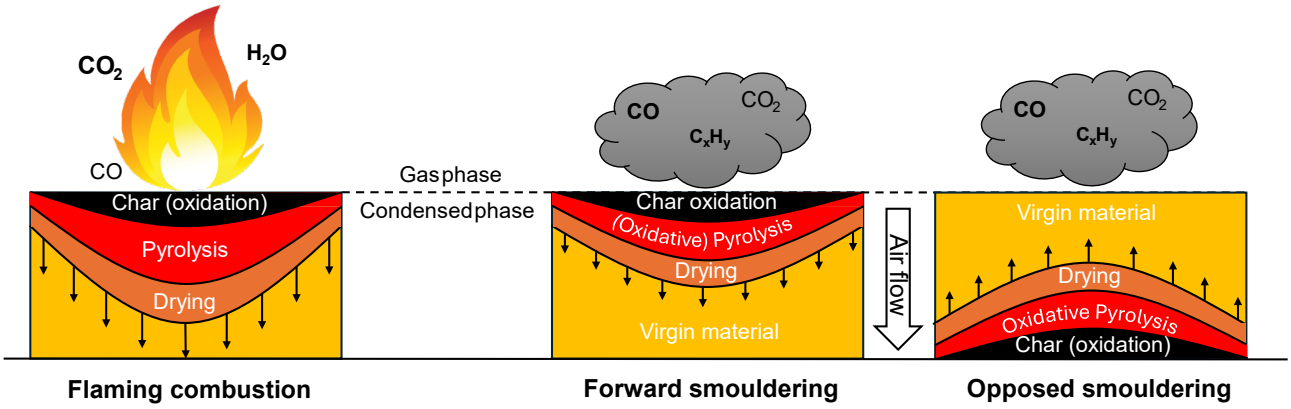


Figure 11: Visualisation of the differences between flaming and smouldering combustion

Flaming combustion is dominated by gas-phase oxidation. Heat from the flame breaks down the solid fuel through pyrolysis, releasing combustible gases and vapours. These mix with oxygen in the surrounding air and burn above the fuel surface. The solid material therefore mainly supplies fuel to the flame. Flaming combustion typically involves high temperatures, rapid reactions and comparatively high heat release rates.

In contrast, smouldering is driven by oxidation at solid surfaces within the material. Oxygen moves through the porous structure and reacts with the original material or with char, the carbon-rich residue formed during thermal decomposition. As smouldering progresses, drying, pyrolysis and oxidation occur in interacting regions. Temperatures and heat release rates are generally lower than in flaming combustion, but the process can sustain itself when sufficient heat is retained to heat and ignite neighbouring material. Its slow progression and lack of visible flames can allow smouldering to remain undetected for extended periods.

Smouldering and flaming combustion represent two distinct combustion regimes with fundamentally different mechanisms, heat-release characteristics, and implications for fire safety

Many bio-based insulation materials are susceptible to smouldering under suitable ignition and exposure conditions. Their lignocellulosic constituents (primarily cellulose, hemicellulose and lignin) provide combustible material, while the porous structure allows oxygen to reach a large internal surface area. Smouldering also occurs in materials such as peat, waste and some thermosetting plastics. Even mineral wool, generally considered non-combustible, can exhibit smouldering when sufficient organic binder is present [20], [22].

Although much of the research has focused on fibrous bio-based insulation, smouldering has also been observed in composites containing plant-based particles embedded in mineral binders. Investigations of hemp-lime composites (hempcrete) demonstrated that self-sustained smouldering can develop under prolonged thermal exposure despite the presence of a non-combustible mineral matrix. The results indicate that surrounding the plant-based constituents with a mineral binder can delay ignition and reduce propagation rates, but does not necessarily eliminate smouldering [23], [24].

3.2. Ignition mechanisms

Smouldering can begin when a material is heated sufficiently for thermal decomposition and oxidation to occur. Oxidation releases heat, while an adequate oxygen supply is needed to maintain the reaction. For smouldering to become self-sustaining, the heat generated must be sufficient to compensate for heat losses and heat adjacent material to the point where it also reacts. Propagation therefore depends on the local energy balance at the reaction front, where smouldering is actively taking place. Heat is transferred away by conduction through the material, convection to the surrounding gases, and thermal radiation. If sufficient heat is retained to sustain reactions in neighbouring material, the smouldering front can advance. Otherwise, it weakens and may eventually extinguish (see Figure 12).

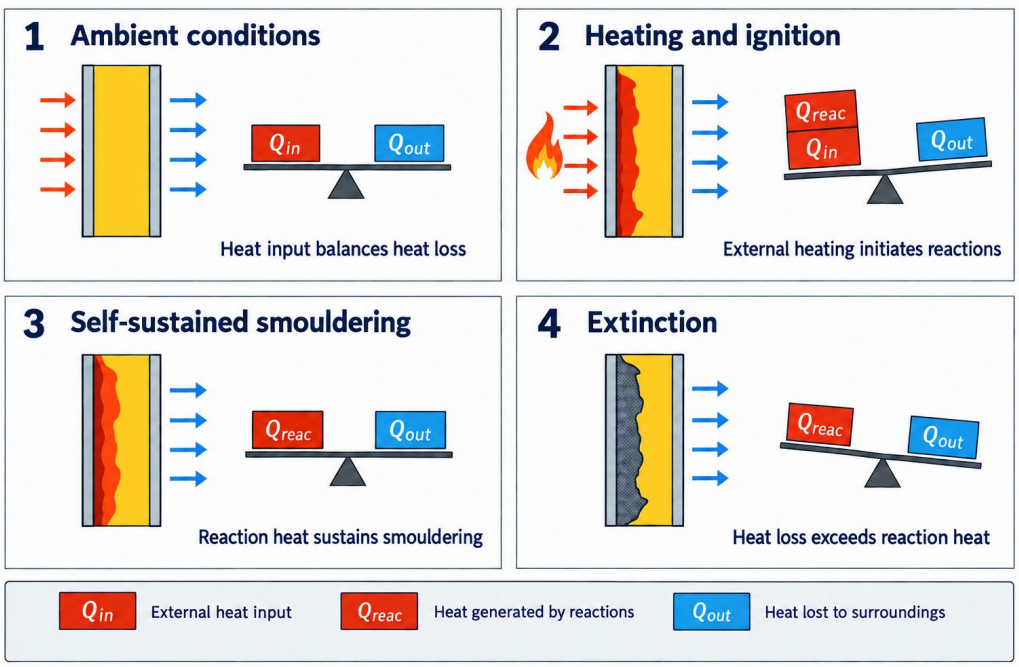


Figure 12: Simplified illustration of the heat balance during heating, ignition, self-sustained smouldering and extinction. Q_{in} represents heat supplied from outside the material, Q_{reac} represents heat generated by reactions within the material, and Q_{out} represents heat lost to the surroundings. The balance symbols illustrate whether heat input and generation outweigh heat losses. Smouldering can continue after the external heat source is removed if the reactions generate enough heat to sustain the process.

Phase 1: At low temperatures, decomposition and oxidation proceed too slowly to generate sufficient heat for self-sustained smouldering.

Phase 2: As external heating raises the temperature, for example during exposure to a compartment fire, thermal decomposition and oxidation become increasingly significant. Decomposition produces combustible gases and char, while oxidation releases heat. The reaction rates increase strongly with temperature, and the insulation begins to generate appreciable reaction heat.

Phase 3: Smouldering becomes self-sustaining when oxidation generates sufficient heat to compensate for heat losses and supply the energy needed to dry and thermally decompose adjacent material. This creates a feedback process: oxidation releases heat, the heat promotes further decomposition, and the resulting char and other reactive material support continued oxidation. The smouldering front can then propagate without continued external heating, provided sufficient oxygen and fuel remain available.

Phase 4: Smouldering weakens when heat generation can no longer compensate for heat losses and the energy required to sustain propagation. This can result from cooling, insufficient oxygen supply or depletion of the available fuel. Reaction rates then decrease, and smouldering eventually extinguishes.

These processes interact, making the energy balance difficult to predict. Experimentally determined ignition temperatures and propagation rates therefore depend on the test conditions rather than being fixed material properties. Important factors include the intensity and duration of heating, oxygen availability, moisture content, specimen dimensions and heat transfer to the surroundings. The advanced models and test methods discussed in Section 5.6 provide approaches for investigating these interactions.

Whether a smouldering fire becomes self-sustaining (progressive) or extinguishes itself is primarily determined by the balance between heat generation, influenced by oxygen, and heat loss.

Heat sources inside and outside a building can initiate smouldering in its construction. A compartment fire can expose adjacent building elements to prolonged heating, potentially exceeding the protection provided by their coverings. Other ignition sources include incorrectly installed fireplaces or flues, electrical faults, lightning-induced currents, and hot works such as torch-applied roofing membranes. These sources can heat combustible insulation or structural components sufficiently to initiate smouldering.

Whether smouldering becomes self-sustaining depends on the materials present, heat transfer and oxygen availability. Combustible insulation, timber framing and other combustible components provide potential fuel. Thermal conductivity and heat capacity influence how heat is transferred and stored, while the intensity and duration of exposure determine the external heat input. Protective layers on both sides of an element affect heat transfer, and cavity ventilation influences both oxygen supply and cooling. Construction details, including joints, mechanical fasteners, cracks and gaps, can create local pathways for heat transfer or air entry. Together, these factors determine whether smouldering dies out or continues to spread within the construction.

The following sections consider ignition and smouldering in building components and the building envelope, including walls, floors and roofs.

3.2.1. Building components

Thermal exposure through protective coverings

The following subsections examine findings from SBI tests, furnace tests and European façade tests involving combustible insulation in building components. The discussion focuses on how thermal exposure, protective coverings and construction details influence ignition and the development of smouldering.

A FRIC study [25] investigated the fire performance of combustible thermal insulation materials through SBI tests on timber frame elements (d = 100 mm) filled with insulation products such as wood fibre and cellulose. The timber frames were protected on both sides by 13 mm gypsum board cladding classified as $K_2$10 / A2-s1,d0. To assess the impact of damage or unsealed penetrations, two openings with a diameter of 168 mm were introduced in the cladding on the fire-exposed side, located in the long wing near the corner.

The specimens were exposed to the SBI burner for 20 minutes, followed by a 10-minute observation period. Visual observations and temperature measurements indicated the onset of smouldering in the areas with penetrations shortly after flame exposure. In contrast, no significant temperature increase was detected beneath intact cladding areas during the 30-minute test. These findings demonstrate that undamaged protective layers with a $K_2$10 classification (or equivalent) can effectively prevent smouldering during the early stages of fire development.



Figure 13: SBI test setup (left) and damage over the surface of the test specimens after test (right) [25]

As part of the HoBraTec research project, 1 × 1 m² timber panel assemblies were subjected to a 30-minute exposure to the standard ISO 834 fire curve in a furnace, representing a fully developed fire with timely intervention. The test panels were built using KVH timber framing (60 × 100 mm) and were entirely filled with wood fibre insulation. Different covering systems were applied, including:

- Single-layer covering with 18 mm fire-rated gypsum board (GKF)
- Single-layer covering with 18 mm GKF + 15 mm OSB board
- Double-layer covering with 2 × 18 mm GKF

Figure 14 presents the isothermal profiles across the insulation thickness during furnace exposure. The results of the first test indicate that a single 18 mm GKF board is insufficient to prevent ignition of wood fibre insulation during a 30-minute exposure to the standard ISO 834 fire curve. The results further confirm that the other covering variants (18 mm GKF + OSB and double-layer GKF) provide clear and reliable protection against ignition—not just for 30 minutes, but well beyond that duration [26].

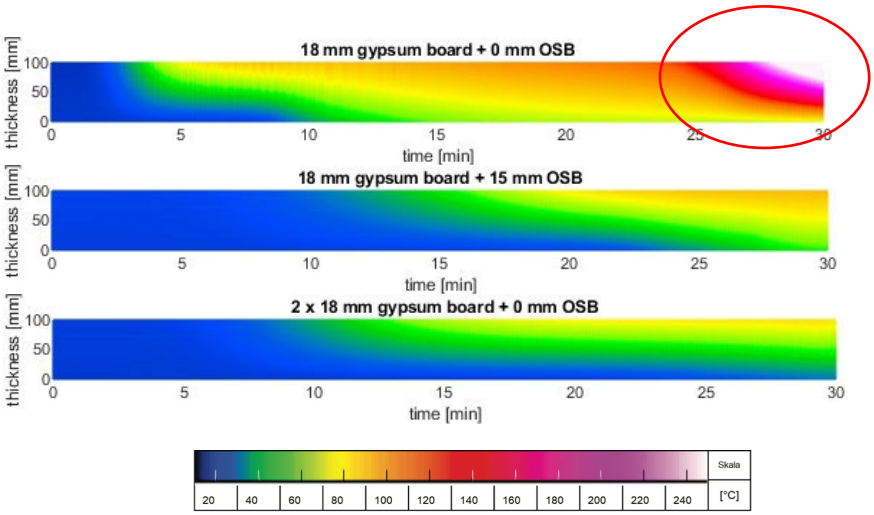


Figure 14: In-depth temperatures for different constructions over 30 minutes of fire exposure [26]

Additional layers, such as installation levels with non-combustible materials, generally improve ignition protection. However, gaps and openings, such as light switches or hollow wall boxes, can reduce the protective effect. In the HoBraTec project, even short-term (30-minute standard-fire-curve) fire exposure led to early ignition of combustible insulation with a penetrated covering. Moreover, smouldering was also observed in assemblies using non-combustible insulation combined with OSB boards.

In the FNR project "Mehr als nur Dämmung," the inclusion of hollow wall boxes caused a clear reduction in ignition resistance, even with two layers of 18 mm gypsum board Type F. This resulted in less than 60 minutes of protection and subsequent smouldering of the renewable insulation. However, when intumescent fire protection boxes were used, self-extinguishment of the insulation could be demonstrated [27].

The WoodUp:High project [28] has conducted 10 full-scale fire-resistance tests on selected walls and decks using various bio-based insulation and covering materials. These constructions are assessed as elements based on load-bearing capacity (R), integrity (E), and insulation (I). Internal thermocouples were placed in the 10 full-scale wall and deck test to gain further knowledge of the layers' fire protection ability. The results showed that composite bio-based structures can readily meet fire-resistance requirements, e.g., REI 60 or REI 90. Thus, the fire performance of bio-based insulation systems is primarily governed by the protective covering system rather than the insulation material itself. Across the tested configurations, the ability to delay heat transfer and protect the underlying combustible insulation varied significantly with the type, number, and combination of layers applied to the fire-exposed side. In all investigated cases, protective layers such as gypsum boards, clay boards, wood fibre boards, or combinations thereof played a decisive role in limiting temperature rise within the construction.

Systems with only limited protection showed relatively rapid temperature increases, with critical temperatures (around 270 °C) reached within less than 10–20 minutes in some layers. In contrast, multi-layered systems significantly improved performance, delaying heat penetration and maintaining temperatures at a moderate level (around 100 °C) for extended periods. Most tested assemblies met the requirements for $K_1 10$ classification, indicating that the substrate is effectively protected during the initial phase of fire exposure. More robust configurations, particularly those combining multiple layers, such as double gypsum boards with additional wood-fibre or clay-based layers, also achieved $K_2 30$ performance, demonstrating sustained protection over longer durations and across a broader range of substrates.

Overall, the results underscore that fire performance cannot be attributed to individual materials alone; it must be assessed at the system level. Especially in the early phase of fire development, intact protective coverings can successfully prevent smouldering. The interaction among covering, insulation, and structural elements determines the overall behaviour, highlighting the importance of tested assemblies and proper detailing to ensure adequate fire safety in constructions using bio-based insulation materials.

The fire performance of bio-based insulation systems cannot be attributed to individual materials alone; it must be assessed at the system level.

Faults in electrical installations

In addition to the context of a room fire, point sources such as faulty electrical installations can also pose a risk of ignition. A series of experiments was conducted to investigate the ignition risk posed by electrical arc faults in timber-frame wall assemblies insulated with wood-fibre insulation as part of a research project [27]. The tests examined arc-fault generation under realistic household electrical loads, the resulting temperatures, the effectiveness of conventional protective devices, and the ignition behaviour of insulation materials.

Stable arc faults produced temperatures exceeding 300°C at distances of up to 30 mm, indicating that ignition cannot be reliably prevented by separation distances alone. Standard circuit breakers and residual-current devices did not interrupt the arc fault directly; instead, disconnection occurred only after secondary insulation damage caused a short circuit. Tests with faulty cables in direct contact with wood-fibre insulation showed no self-sustained burning or smouldering following 25 ± 2 s of arc-fault exposure and a subsequent 15–20-minute observation period, although substantial local charring occurred with PVC-insulated cables (see Figure 15). A reference test with hemp-fibre insulation showed similar behaviour. Extending the exposure to 45 ± 2 s in a wood-fibre specimen resulted in self-sustained smouldering. A corresponding longer-duration test with hemp-fibre insulation was not reported.

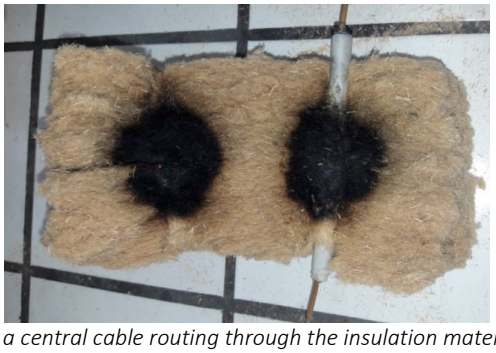


Figure 15: Charring of a central cable routing through the insulation material (NYM-J cable) [29]

Additional tests with PVC conduit and within a representative timber-frame wall assembly showed that the conduit provided only short-term protection before burning through. Overall, the experiments demonstrated that arc faults can represent a potential ignition source for bio-based insulation materials, particularly if the fault persists for an extended period, while early fault detection and disconnection significantly reduce the risk. In properly installed electrical systems, the risk of arc-fault ignition within wall constructions is generally considered low, as cables are exposed to minimal mechanical stress under normal service conditions. The risk can be further mitigated through early fault detection and rapid isolation of the faulty circuit [27].

Persistent electrical arc faults can initiate smouldering in bio-based insulation. Early fault detection and rapid disconnection of the affected circuit can reduce this risk.

Thermal exposure at penetrations

Wood stoves are known ignition sources, particularly when combustible materials are located too close to the roof and floor chimney penetrations. Although certified chimneys, certified stoves, and prescribed safety distances help reduce the risk, they do not eliminate it, especially if installation conditions significantly differ from test scenarios such as EN 1859 [30].

As part of a DBI research project, full-scale experiments were carried out using a realistic chimney–roof assembly. Based on incidents documented by DBI's fire investigation unit, the project aimed to determine whether additional insulation layers around a chimney floor penetration can contribute to the development of a fire. The inner diameter of the chimney was 160 mm, and it was insulated using a non-combustible tube with a minimum thickness of 60 mm. The chimney was heated using an LPG burner. During one- and four-hour controlled heating periods, the upper section reached 500 °C, which is representative of a typical wood fire load. The oven's nominal heat output was 4.5 kW, with an efficiency of 76%. The roof assembly consisted of a timber frame filled with mineral wool insulation and clad with chipboard. An additional layer of cellulosic insulation was added on top (see Figure 16).

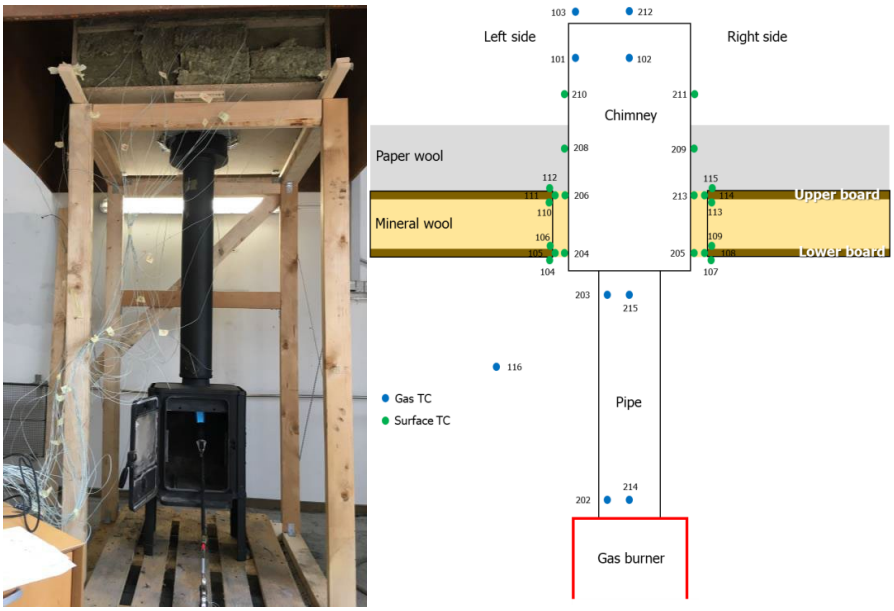


Figure 16:Test setup for chimney-roof configuration at DBI

During the one-hour heating period, the surface temperatures of the mineral and cellulose insulation materials increased similarly, and no ignition was observed. During the 4-hour heating period, the cellulosic insulation exhibited smouldering behaviour, reaching 250-300 °C after around 3.5 hours (see Figure 17). However, it was not possible to determine whether the mineral wool with organic binders contributed to the ignition. The results showed that a 60 mm distance was insufficient to prevent ignition of the additional cellulosic insulation material on the roof.

Adding insulation around an existing chimney penetration can alter heat transfer and reduce heat dissipation, potentially increasing temperatures in adjacent combustible materials.

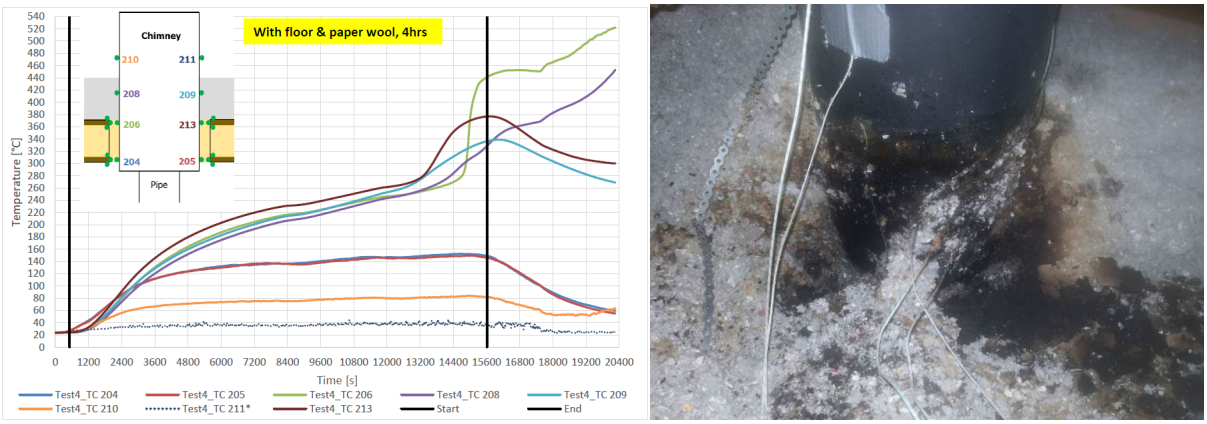


Figure 17: Results of temperature measurements on chimney surface, test with floor & insulation - paper wool, 4-hours burning (left) and photo of the insulation after the test (right)

Penetrations and recessed installations require particular attention in constructions containing combustible insulation. Besides chimneys, relevant details include ventilation ducts, pipes, electrical cables and installation boxes. Their performance depends on the interaction between the installation, its protective measures and the surrounding construction.

Within DBI's WoodUp:High project [28], a comparative fire test investigated identical pipe penetration seals and electrical installation boxes in two timber-frame walls, insulated with either stone wool or wood-fibre batts. Both walls were protected on each side by two layers of 12.5 mm gypsum board. The pipe penetrations were tested according to EN 1366-3, while the electrical installation boxes were assessed using the principles of EN 1364-1. During the 91-minute test, the pipe penetration seals maintained integrity in both wall constructions. The insulation criterion was maintained until the end of the test, except at one penetration in the wood-fibre wall, where failure was recorded at 90 minutes. However, the unexposed-side electrical installation box in the wood-fibre wall lost integrity after 72 minutes, with sustained flaming and an opening recorded. The corresponding box in the stone-wool wall maintained integrity throughout the test.

These findings demonstrate that penetration seals and recessed installations should be assessed in conjunction with the surrounding insulation and wall construction. They provide evidence for the specific details tested, rather than a general approval for use with bio-based insulation. A practical challenge remains ensuring that the documented field of application of a proposed system explicitly covers the intended construction. However, the integrity (E) and insulation (I) criteria assessed in conventional penetration-seal tests such as EN 1366-3 do not directly assess ignition or smouldering within the building component. Demonstrating fire resistance at a penetration does not, on its own, demonstrate that concealed combustion is prevented or that smouldering will cease after the external fire exposure ends.

3.2.2. Building envelope

Façade systems can be grouped into generic types according to their construction and how they provide thermal insulation, manage moisture and protect against weather (Figure 18):

a) **Monolithic façades:** Solid wall systems, typically constructed from masonry or concrete.
b) **Cavity walls:** Inner and outer wall leaves, commonly constructed from masonry or concrete, separated by a cavity that may contain insulation.
c) **External thermal insulation composite systems (ETICS):** Insulation fixed to a supporting wall and protected by a reinforced base coat and finishing render.
d) **Metal-faced sandwich panels:** An insulating core between two thin metal facings.
e) **Ventilated façades:** A supporting wall and insulation layer combined with an external rainscreen, separated from the underlying construction by a ventilated air gap.

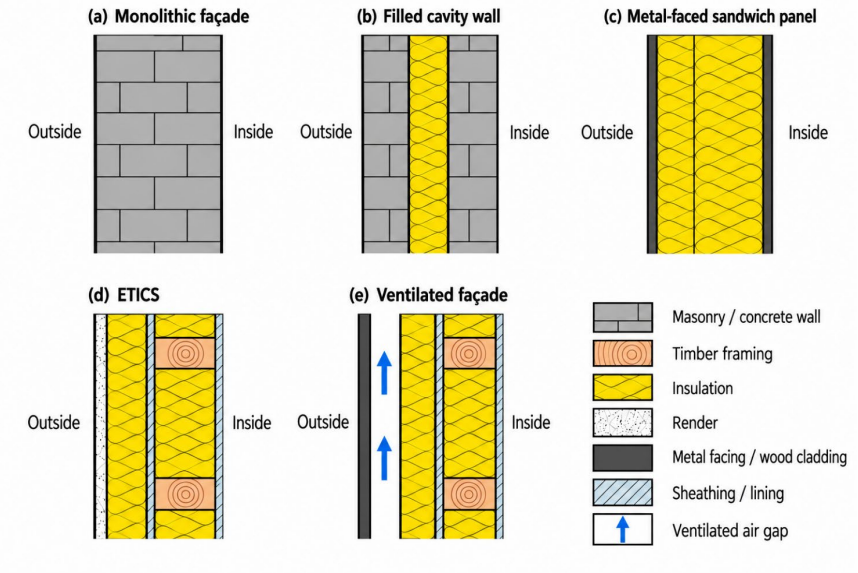


Figure 18: Cross sections of different generic types of facade systems

Various fire scenarios may cause ignition of combustible insulation in the building envelope (see Figure 19), such as

- Fires originating outside the building, such as burning waste containers;
- Fires in adjacent buildings, exposing the envelope to radiant heat and wind-borne embers;
- Fires originating inside the building, such as compartment fires spreading through openings;
- Lightning-induced ignition;
- Fires involving photovoltaic (PV) installations or other rooftop technical equipment;
- Hot works during construction, maintenance or repair, such as torch application of roofing membranes.

The following sections describe the most relevant façade types and discuss different ignition scenarios for bio-based insulation materials.

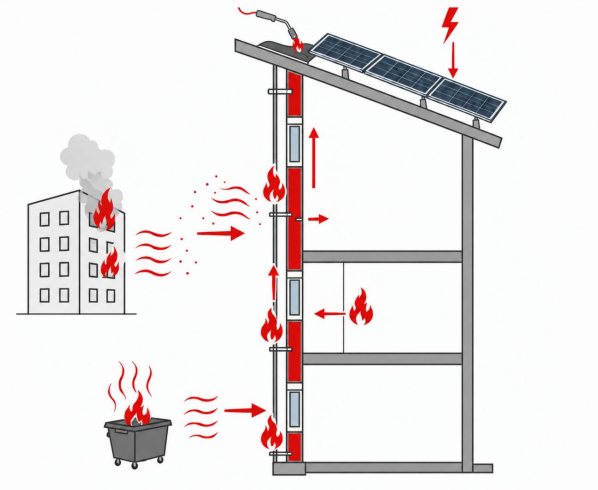


Figure 19: Examples of fire scenarios that may lead to ignition of combustible insulation within the building envelope

External thermal insulation composite systems

Rigid wood-fibre insulation boards are commonly used in external thermal insulation composite systems (ETICS), where they serve as a substrate for render and plaster layers. Small-scale cone calorimeter experiments on rendered wood-fibre boards exposed to an external heat flux of 40 kW/m² demonstrated that smouldering ignition occurred at temperatures of approximately 350 °C [31]. However, signs of thermal degradation were observed at substantially lower temperatures. Visible discolouration, pyrolysis, and the release of smoke gases were already evident at around 250 °C (Figure 20), indicating that significant thermal decomposition can precede the onset of self-sustained smouldering combustion.

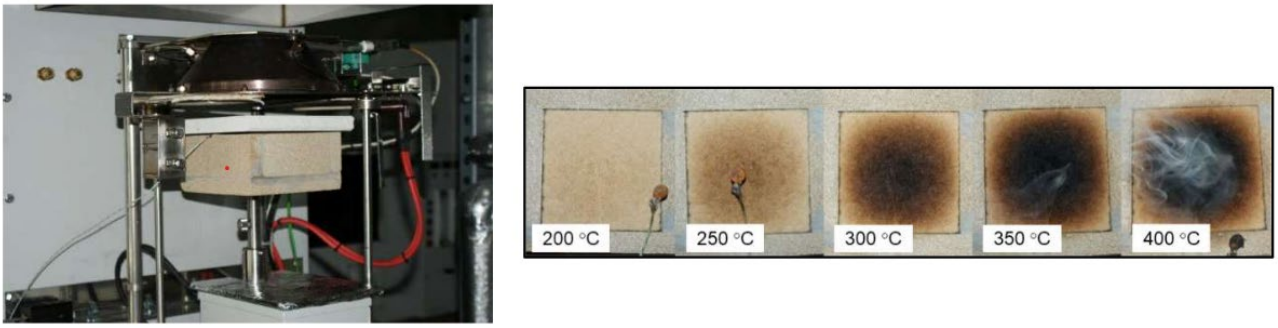


Figure 20: Test setup in the cone calorimeter (left) and surface of the wood fibre insulation material under the cover after reaching the temperature shown (right) [31]

The time to ignition was found to depend primarily on the type and thickness of the plaster layer. Figure 21 summarizes the performance of the different plaster systems and layer thicknesses investigated. The results clearly demonstrate that plaster thickness is the dominant parameter governing fire protection performance, with increasing thickness significantly delaying heat penetration into the underlying insulation. However, the relatively high thermal mass of the plaster layer should also be considered, as it can store substantial amounts of heat and subsequently transfer it to the insulation after the external heat source has been removed. Consequently, delayed temperature increases and potential smouldering initiation may occur even after flame extinction, for example following a façade fire.

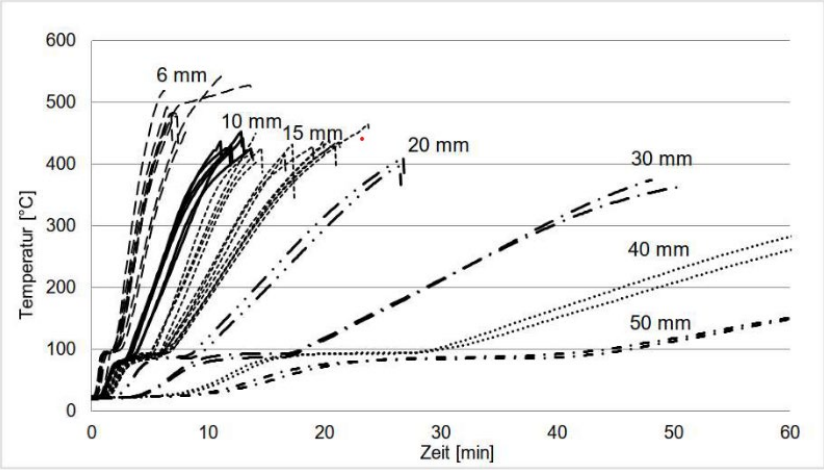


Figure 21: Temperature development, below plaster samples of different composition and thickness at around 40 kW/m² [31]

To evaluate the fire protection performance of wood-fibre ETICS incorporating a thick-layer render, large-scale fire tests were conducted in accordance with DIN 4102-20 (Figure 22). The 25 mm render system was specifically designed to limit temperatures within the wood-fibre insulation to below the critical threshold for smouldering ignition, approximately 350 °C.

However, preliminary investigations revealed that additional protective measures were required in the vicinity of the fire source, particularly around the burner opening, where the façade is most severely thermally exposed. Consequently, non-combustible stone wool boards were installed as lintel and reveal protection, as achieving sufficient resistance to direct flame impingement through increased render thickness alone was considered impractical and economically unfeasible.

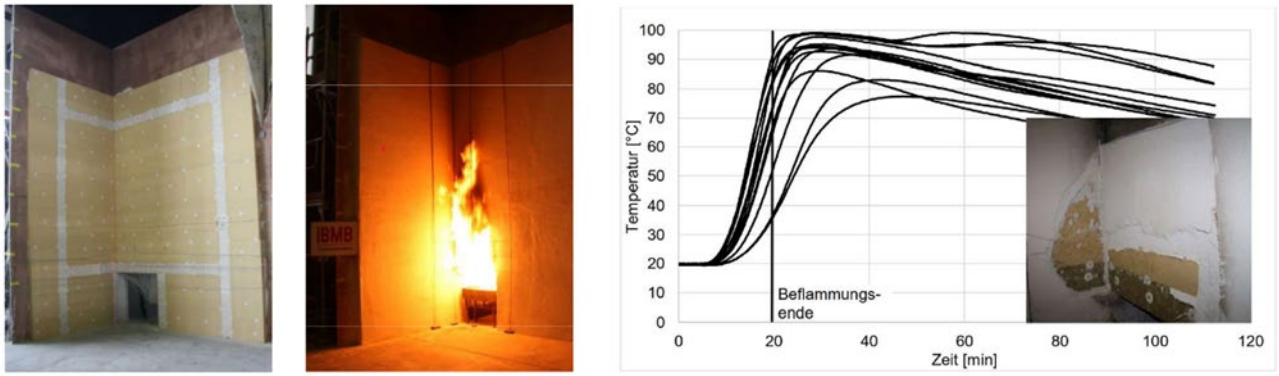


Figure 22: Unplastered insulation layer (left), plastered wood fibre ETICS during flame treatment (middle) and temperature recording below the 25 mm plaster layer in the lintel area on stone wool (grey lines) and on wood fibre insulation boards (black lines) (right) [31]

In the façade fire test conducted on the test rig, the target render thickness was 25 mm, with measured values ranging between 23 mm and 35 mm. During the 20-minute flame exposure and the subsequent approximately 45-minute observation period, the insulation temperature remained below the critical threshold of 350 °C, and a transition to the cooling phase was observed. The highest temperatures on the wood fibre insulation (approximately 275 °C) were recorded at a height of about 0.5 m above the fire chamber opening and roughly 0.75 m from the inner corner of the test setup. Overall, the results demonstrate that the render system provided effective thermal protection under the tested conditions.

Rear-ventilated facades

Large-scale façade fire tests based on the emerging European façade test method were conducted within the BioFacades:UpHigh project at DBI [32]. The tested assemblies consisted of wood-clad rear-ventilated façades mounted on timber-frame wall cassettes containing bio-based insulation materials such as wood fibre and cellulose. The insulation was enclosed within a timber frame and protected externally by windbreaker boards and an aluminium-faced membrane located behind the wooden façade cladding. The insulation was enclosed within a timber frame and protected externally by wind-barrier boards. Various wind-barrier materials were evaluated between the insulation layer and the ventilation cavity. An aluminium-faced membrane was additionally installed behind the wooden façade cladding in the two tests using wood-fibre wind-barrier boards. The configuration enabled the investigation of both external flame spread along the façade surface and concealed fire development within the cavity and insulated wall assembly.

In principle, non-combustible wind barriers provide an additional protective layer against direct thermal exposure. However, the fire exposure near the combustion chamber was sufficiently severe (compared with other façade tests such as DIN 4102-20) to cause local burn-through of the façade layers in all tests, regardless of the wind barrier type. As a result, smouldering was observed in all assemblies that used bio-based insulation materials.

Once initiated, smouldering propagated slowly through the insulation layer at approximately 5-10 cm/h. Smouldering was primarily observed in areas subjected to prolonged façade burning, see Figure 23. The low propagation rate and limited heat release resulted in relatively low temperatures on the cold side of the wall assembly. Consequently, no complete burn-through of the insulated wall cassettes was observed during the 60-minute test. The full test reports are available online [33].

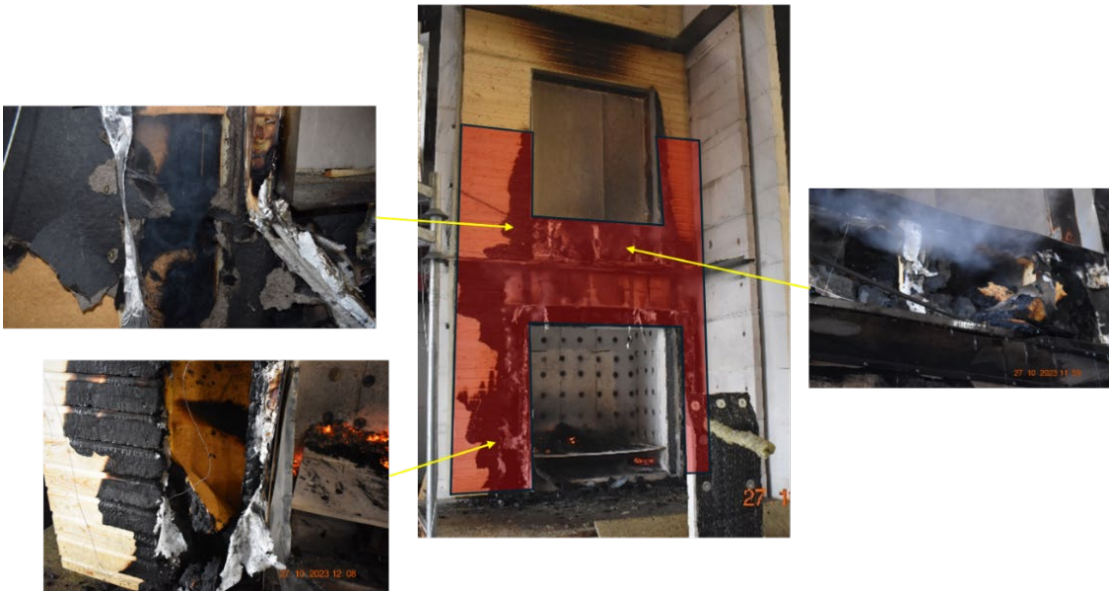


Figure 23: Areas affected by smouldering after 60 minutes fire exposure in the European façade test (BioFacades:UpHigh Test 3)

Steel-envelope / Sandwich panel systems

In [34], five steel-based building envelope systems incorporating bio-based insulation were investigated, comprising both prefabricated sandwich panels and site-assembled façade constructions. Various fire tests were conducted to determine reaction-to-fire and resistance-to-fire behaviour, as well as scenarios for external fire exposure, such as ISO 13785-1 and CEN/TS 1187.

Two of the systems consisted of factory-produced sandwich panels with steel facings and a 150 mm thick wood-fibre insulation core: a wall cladding panel (System 1) and a profiled roofing panel (System 2). The remaining three systems included a double-skin façade with wood-fibre insulation and an overall thickness of 265 mm (System 3), a façade system with boarded plank cladding and 30 mm bio-based insulation boards combined with wood-fibre insulation (System 4), and a flat roof sandwich panel comprising steel facings and a 200 mm wood-fibre core, supplemented on site with mineral wool and a waterproof membrane (System 5)

Based on the reaction-to-fire tests, the sandwich panel systems (Systems 1, 2, and 5) achieved a classification of B-s1,d0, whereas the double-skin metal sheet façade systems (Systems 3 and 4) were classified as B-s2,d0. However, progressive smouldering was detected after the regular end of the test, using a thermal imaging camera, see Figure 24 to Figure 26.

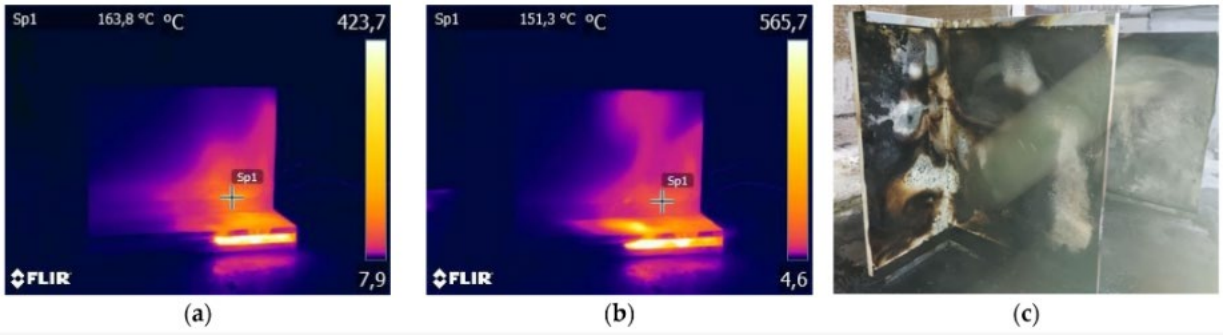


Figure 24: Images of the double skin cladding (systems 3 and 4):(a) 1 h after the test; (b) 1.5 h after the test; (c) 17 h after the test [34]

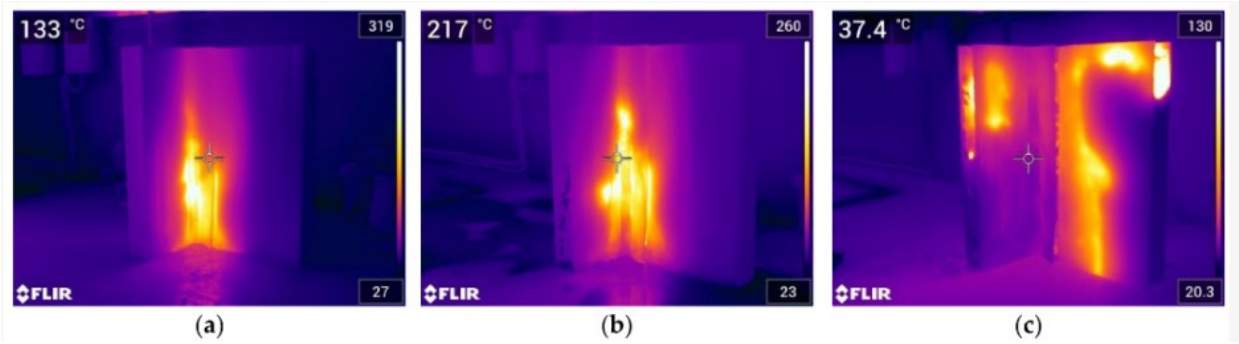


Figure 25: Images of the sandwich panel (system 5): (a) 1 h after the test; (b) 4 h after the test; (c) 19 h after the test [34]

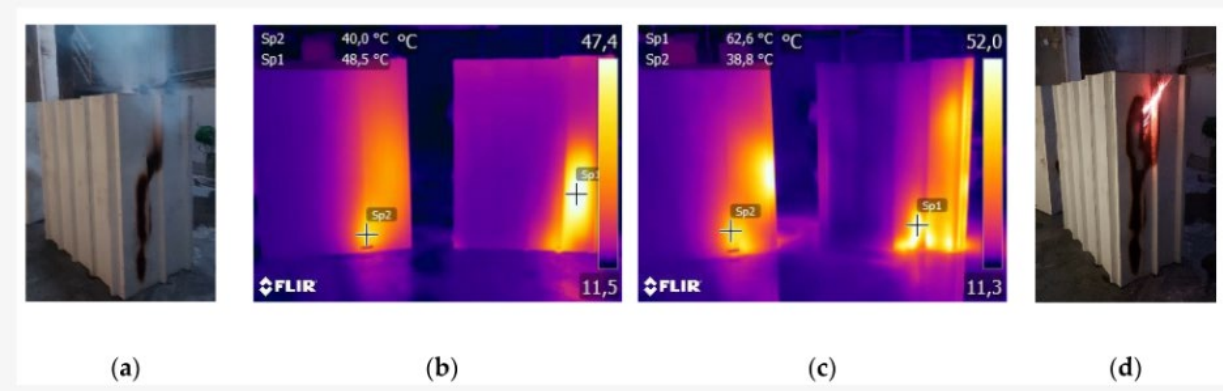


Figure 26: Images of the sandwich panel (system 2): (a,b) after the test; (c,d) 2 h after the test [34]

The results demonstrate the discrepancy between reaction-to-fire performance and smouldering behaviour. The steel facings limit direct flame involvement of the insulation and thereby contribute to favourable reaction-to-fire performance. However, efficient heat transfer through the steel layers can expose the wood-fibre core to elevated temperatures early in the fire, potentially triggering smouldering combustion despite the absence of significant flaming.

While the SBI test classified the investigated systems as Class B products, indicating limited heat release and favourable fire performance during the early stages of a flaming fire, it does not assess the potential for smouldering ignition and propagation. As a result, the SBI test alone cannot provide a comprehensive assessment of the fire safety of bio-based insulation materials, particularly in applications where concealed smouldering and delayed fire development may occur.

Lightning-induced ignition

In [35], a series of tests was carried out to determine whether the energy from a lightning current can cause smouldering or ignition in various insulation materials. The study examined several common bio-based insulations, such as wood fibre, hemp, cellulose, cork, and sheep wool, in different installation configurations. Within the scope of the study, four typical fault scenarios were considered, see Figure 27.

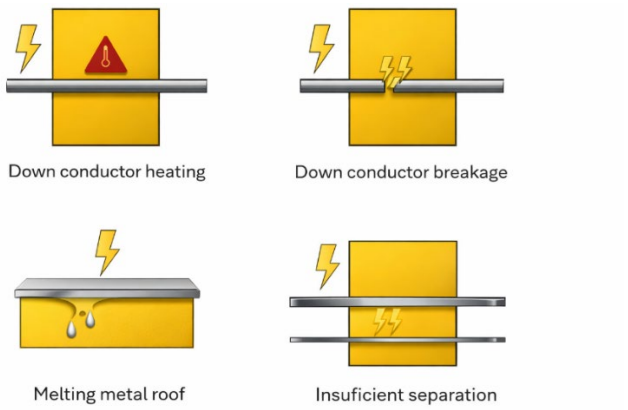


Figure 27: Different scenarios that could cause ignition in bio-based insulation due to lightning strikes.

Heating of an intact down-conductor caused no ignition in any of the specimens tested under that scenario. External arcing produced different outcomes depending on the product: both hemp products and the jute/hemp product ignited, whereas the tested wood-fibre boards, cork and sheep-wool specimens did not ignite under the investigated conditions. Molten-metal droplets caused local ignition in all products tested under that scenario except cork, although the flames generally extinguished after a few seconds.

Arcs passing through the insulation, representing insufficient separation distances or absent external lightning protection, caused ignition in several products, including both hemp products and multiple wood-fibre boards. For loose cellulose, loose wood fibre and cork, no ignition threshold could be established because the specimens were disrupted by the arc pressure at higher current amplitudes; no ignition occurred at the lower amplitudes tested. These results demonstrate that ignition behaviour depends on both the specific product and the mechanism of lightning-current exposure [35].

Arcs from lightning strikes can act as ignition sources for bio-based insulation materials.
A properly installed lightning protection system can effectively reduce the likelihood.

3.3. Consequences of smouldering

3.3.1. Smouldering propagation

The smouldering propagation rate and temperature development depend strongly on material properties and boundary conditions, particularly material type, bulk density, imposed heat flux, and oxygen availability. For uncovered insulation materials, typical smouldering temperatures range between approximately 400 and 700 °C, depending on the material composition and ventilation conditions. Smouldering tests conducted in accordance with EN 16733 reported propagation velocities between 1.7 mm/min and 10.5 mm/min for various types of bio-based insulation, see Table 2. The observed variation reflects differences in density, porosity, and material formulation. The results are not intrinsic material constants or a ranking of material categories. Tube furnace experiments with defined ventilation rates demonstrated that, for loose-fill insulation materials, the smouldering velocity increases nearly linearly with airflow velocity [36]. Tests in a façade test with ETICS showed significantly slower propagation rates of approximately half a meter per day [31].

Table 2: Smouldering propagation velocities for selected bio-based insulation products in tests according to EN 16733

Material and product form	Density (kg/m³)	Average smouldering velocity (mm/min)
Wood-fibre mat	52	5
Wood-fibre board	194	2.5
Loose-fill hemp	50	9.2
Hemp-fibre board	100	1.7
Hemp-fibre mat A	40	—[1]
Hemp-fibre mat B	30	10.5
Loose-fill cellulose	50	2.7
Cellulose mat	69	2.8
Loose-fill seagrass	70	2.9

[1]The tested specimens self-extinguished before sustained propagation through the specimen. Sources: [27] and [37]

The smouldering propagation across timber-frame wall assemblies was investigated as part of the HoBraTec [26] project. Tests on 1 m x 1 m timber frame components demonstrated that, in the event of a short, intense room fire, cavity fires can ignite through small openings in the fire-protection cladding and continue to smoulder independently for a longer period (>18 hours). In the individual experiment outlined here, a timber-frame component consisting of a 100 mm-thick frame, 15 mm-thick OSB cladding on both sides mounted on stone wool, and 18 mm-thick gypsum cladding on both sides was exposed to the standard ISO 834 fire curve for 30 minutes.

After exposure to fire, the component was removed from the furnace and observed for 20 hours. To ensure that the fire penetrated the component, which was divided into two parts by a central support, the cladding layers on the fire room side were provided with a drill hole for electrical installations (d = 68 mm). The test aimed to establish whether the OSB board would ignite and begin to smoulder when exposed to fire, regardless of the combustibility of the insulation. Thermal imaging was used to monitor the progression of the smouldering fire on the component's fire-facing surface. The results are shown in Figure 28. The photo shows the component after the observation phase was completed and the gypsum cladding was removed.

The diagram shows the approximate progression of the burn front based on thermal image analysis. A temperature of 100 °C on the gypsum surface was assumed as the criterion for ignition.

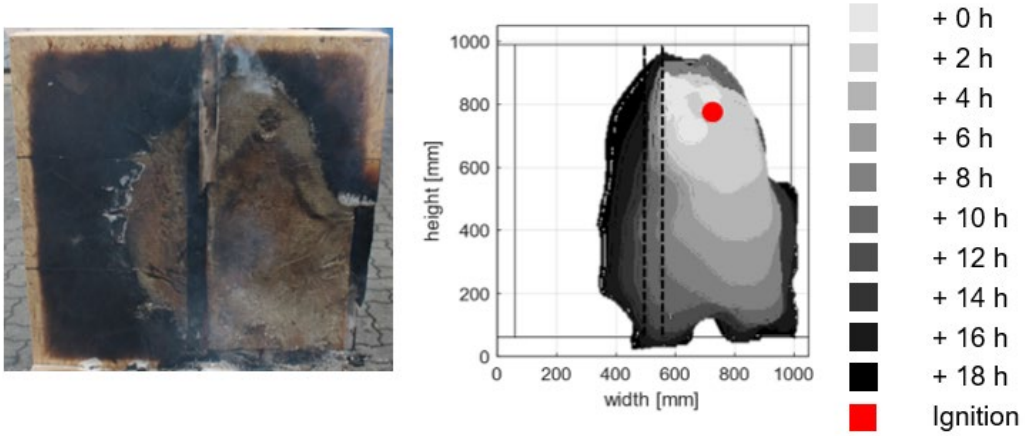


Figure 28: Results from HoBraTec [26] experiments on the smouldering behaviour of OSB boards mounted on stone wool. Left: Photo of a wood panel component after 20 hours of smouldering fire on an OSB after 30 minutes of standard ISO 834 fire curve exposure. Right: Spread of smouldering fire on the OSB over 18 hours.

This test was repeated using a component insulated with wood fibre insulation. The results are shown in Figure 29, analogous to those for the component with stone wool. The results indicate that the wood fibre insulation significantly increases the spread rate of the smouldering fire, even beyond the compartment partition. Fire propagation into the adjacent compartment occurs after just 8 hours.

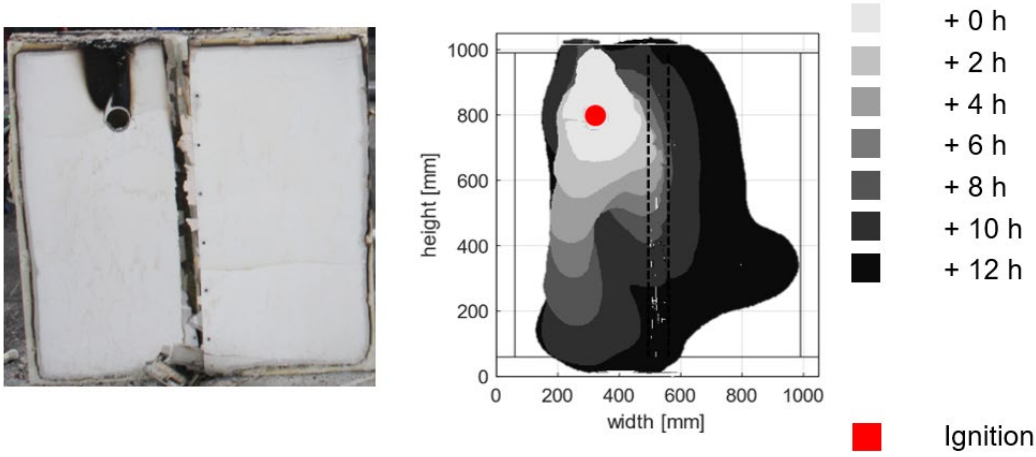


Figure 29: Results from HoBraTec [26] experiments on the smouldering behaviour of OSB boards mounted on wood fibre insulation. Left: Photo of a wood panel component after 20 hours of smouldering fire on an OSB-board after 30 minutes of standard ISO 834 fire curve exposure. Right: Spread of smouldering fire on the OSB-board over 12 hours.

The propagation of smouldering in ETICS was investigated using a modified EN 16733 smouldering test setup, as described in [27]. In deviation from the standard procedure, rendered specimens were examined (see Figure 30) to represent realistic façade configurations. The wood fibre insulation boards were fully enclosed within a rendering system comprising gypsum boards and a mineral adhesive, thereby simulating their end-use application in ETICS. The specimens were externally ignited until smouldering initiated within the insulation layer, and subsequently monitored for three to five days until self-extinction occurred. The rendered specimens exhibited irregular and non-uniform smouldering fronts, indicating complex internal propagation mechanisms.



Figure 30: Plastered test specimen after flame treatment (left), and four typical smouldering processes after the end of the test in the middle of the wood fibre insulation material [31]

Additional EN 16733 tests were conducted to assess mitigation measures, incorporating a dedicated smouldering barrier. (Figure 32, red lines). Temperature measurements taken above the barrier on the protected side (Figure 32, green lines) showed maximum values of approximately 90 °C for a barrier height of 50 mm. Under these conditions, no smouldering propagation into the upper insulation layer was observed, demonstrating that the barrier effectively interrupted vertical smouldering spread at the tested scale.

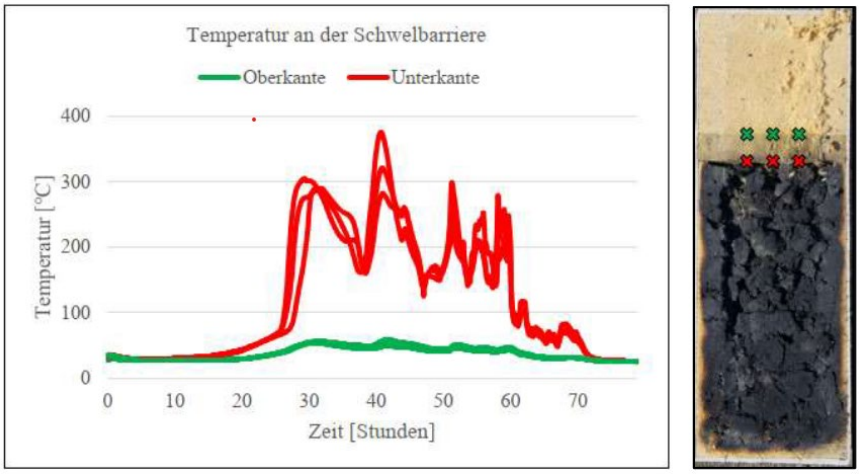


Figure 31: Temperature recording of a plastered smouldering barrier (left) and plastered smouldering barrier test specimen, after the end of the test, opened in the middle of the insulation material (right) [31]

Complementary to the small-scale investigations, a large-scale façade fire test was conducted using a façade test rig in accordance with DIN 4102-20. The tested system consisted of wood fibre insulation boards with integrated smouldering barriers (height 200 mm), covered by a nominally 6 mm thin-layer plaster system [31] (Figure 32). Post-test measurements revealed significant variability in plaster thickness, ranging from 3 mm to 14 mm. The ETICS was installed on a timber substructure with double-layer gypsum plasterboard lining.



Figure 32: DIN 4102-20 test with wood fibre ETICS with thin-layer plaster system (from left to right) Unplastered insulation layer, during and immediately after flame treatment and opening of the system at the end of the test [31]

The initial smouldering region developed within the direct flame exposure zone. From there, smouldering propagated within the insulation layer as shown in Figure 33. The process was monitored for approximately 75 hours until the test was terminated due to extensive thermal degradation.

The results indicate that the observed propagation along the short leg of the façade rig, extending beyond the lowest barrier (Figure 33, right), was attributable to thermal decomposition of the wood-based sheathing panel rather than continued propagation within the insulation. At other locations, smouldering spread upward only until reaching the installed barriers and did not extend beyond them. This demonstrates that the smouldering barriers effectively limited vertical propagation within the insulation layer.

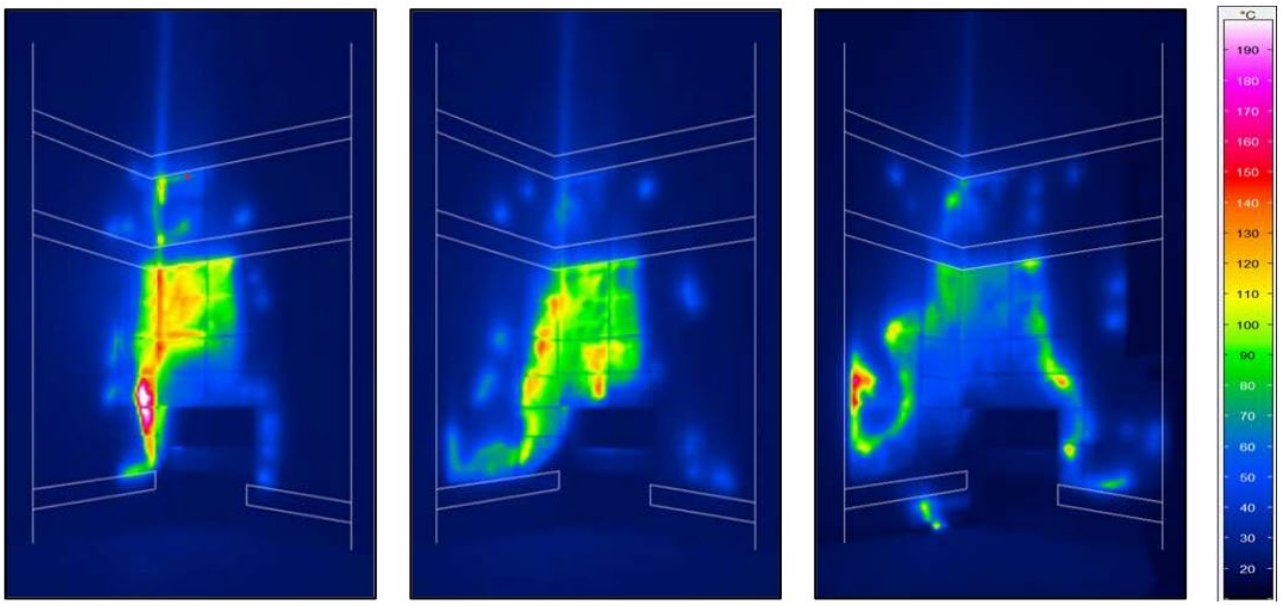


Figure 33: Thermal images of the large-scale fire test with 6 mm thin-layer plaster system with smouldering barriers indicated by lines (from left to right) approx. 4 hours, 40 hours and 75 hours after flame treatment [31]

In a recent project [38], large-scale façade fire tests on wood fibre insulation external thermal insulation composite systems were performed on a European large-scale façade test and a test according to DIN 4102-20. The primary objective was to investigate the fire behaviour of these systems, with particular emphasis on temperature development and smouldering processes within the façade assembly. A key aspect was extending the post-fire observation period to up to three weeks.

The results showed that, following the initial fire exposure, smouldering processes can persist and propagate within the insulation layer and façade system over extended periods. These processes were spatially and temporally heterogeneous, with distinct zones of smouldering, glowing, and flaming combustion identified within the façade assembly (see Figure 34). The preliminary findings indicate that fire behaviour in wood fibre-based ETICS cannot be fully captured by short-duration fire tests alone, as significant degradation and heat development may persist long after visible flames are extinguished.

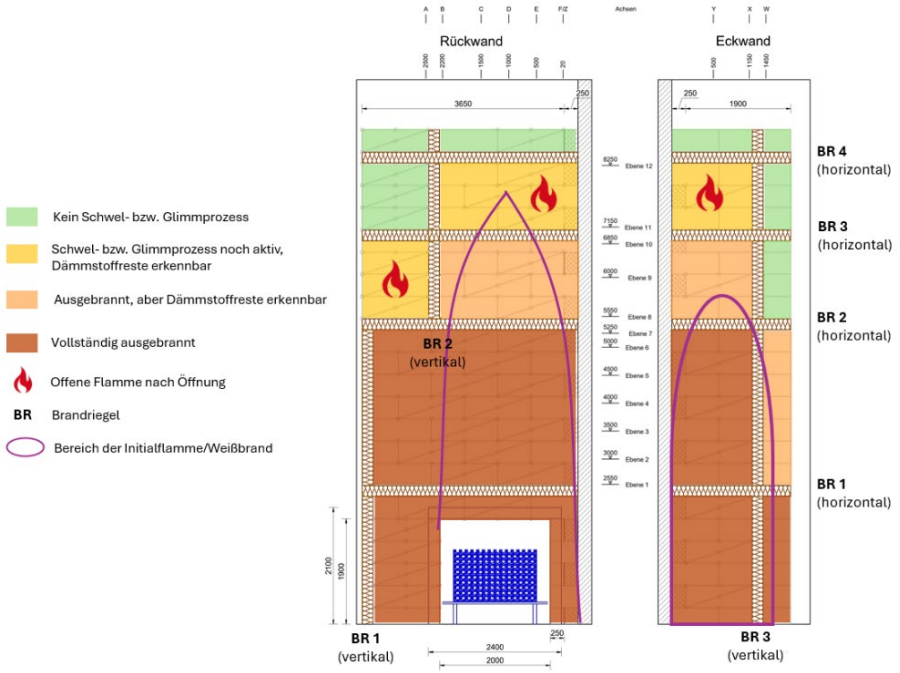


Figure 34: European façade test with wood fibre ETICS, showing the damage patterns observed after the fire test (> 3 weeks), purple: initial flame exposure, yellow: active smouldering, brown: partly/fully burned-out areas [38] (Bachelor's thesis Michelle Rosin)

3.3.2. Impact on structural integrity and compartmentalisation

Recent research projects, such as *Wood:UpHigh*, have demonstrated that, when properly designed, timber-frame constructions incorporating bio-based insulation materials can achieve a fire-resistance rating of more than 60 minutes. However, it must be acknowledged that standard fire resistance test methods typically verify structural and separating performance only for the duration of exposure to the standard temperature-time curve, e.g. limited to 60 or 120 minutes. As mentioned in Section 2.1.2, these tests do not replicate 'real' fire exposure, including the post-fire cooling phase, during which critical degradation mechanisms may still occur.

The influence of smouldering and cavity fires on the residual load-bearing capacity of structural elements remains insufficiently understood. If smouldering combustion does not self-extinguish, progressive structural damage cannot be excluded. Full-scale furnace experiments reported in [39] show that timber columns may fail not during the heating phase, but during the subsequent cooling phase, even when the heating duration corresponds to only approximately 25% of the nominal fire resistance time.

In these experiments, column instability developed hours after the primary fire exposure had ended, driven by continued smouldering and delayed strength loss. Importantly, the studies also indicate that timely firefighting intervention was crucial in preventing complete structural collapse. Although these experiments did not specifically involve cavity fires with bio-based insulation, they clearly demonstrate that smouldering processes can significantly weaken timber structures long after visible flames have been extinguished.

The effects of smouldering within the timber itself, rather than within combustible insulation, were further investigated in [40]. Three full-scale natural fire experiments were conducted using a partially protected mass timber floor assembly (40-20-20-20-40 mm) installed above a compartment measuring 34.3 m × 10.3 m × 3.1 m. In addition, two non-load-bearing glulam columns were included in the setup. A pronounced tendency for smouldering was observed particularly at corners and joints, which was attributed to increased heat accumulation in these regions. Although the experiments did not specifically address concealed-space fires, they demonstrated that smouldering can continue for hours or even days after visible flaming has ceased and may result in progressive structural degradation of load-bearing timber elements.

The HoBraTec research project provided further evidence of this mechanism. In this study, ignition of wood fibre insulation concealed within a building component led to sustained smouldering combustion of a centrally installed wooden stud. Two otherwise identical timber panel assemblies (1 m × 1 m), differing only in the insulation material, were exposed to the standard ISO 834 fire curve for 30 minutes in a furnace. One assembly contained wood fibre insulation, while the reference assembly used stone wool with a melting point above 1000 °C. After furnace exposure, both components were surface-extinguished and monitored for more than 20 hours during the cooling phase.

While the externally extinguished surfaces showed no immediate signs of damage, the component insulated with wood fibre exhibited elevated internal temperatures and intermittent smoke release during cooling. Subsequent opening of the assembly revealed extensive smouldering of both the wood fibre insulation and the centrally positioned timber stud (see Figure 35). In contrast, the assembly insulated with stone wool remained largely undamaged, with no signs of internal smouldering. These results illustrate that standard fire resistance tests may underestimate post-fire structural risks, particularly in assemblies containing bio-based insulation materials that can sustain smouldering combustion. They further emphasize the importance of considering the cooling phase, cavity conditions, and firefighting measures when assessing the structural integrity of timber constructions exposed to fire.

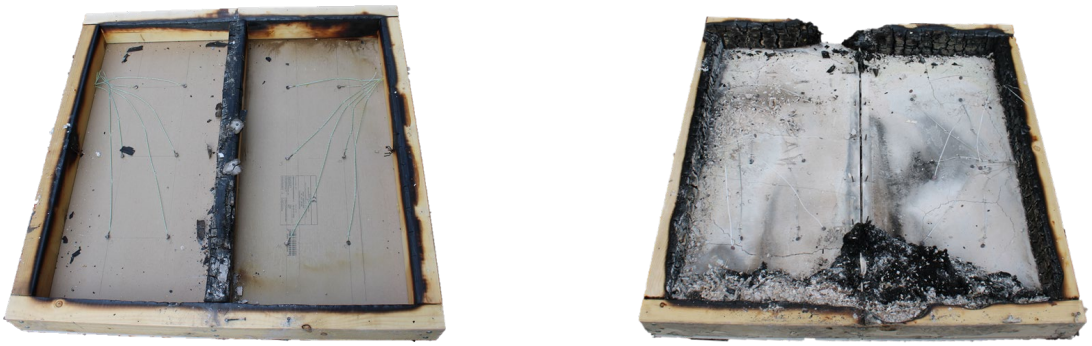


Figure 35: Photographs of timber panel components following fire exposure and a 20-hour observation period, with a construction identical in all respects except for the insulation material. Left: stone wool; Right: wood fibre insulation

Concealed smouldering can weaken structural elements during the cooling phase. This highlights the importance of effective firefighting operations and the consideration of the post-fire phase.

3.3.3. Release of carbon monoxide and other toxic gases

Smouldering combustion in bio-based insulation is characterised by incomplete oxidation and therefore produces comparatively high yields of carbon monoxide (CO) [41]. CO is a colourless, odourless, and non-irritating gas, which makes its presence difficult to detect without monitoring. Despite these properties, it is highly toxic and can cause severe or fatal poisoning at relatively low concentrations. According to the Acute Exposure Guideline Levels (AEGL-2), a concentration of 420 ppm over 10 minutes can already cause severe health effects, including loss of consciousness [42].

During emergency responses, fire departments have observed that CO can spread beyond the immediate damage area by diffusing (or permeating) through walls and ceilings, as confirmed by several experiments [43]. The Institute of Fire and Civil Protection Heyrothsberge (IBK) conducted studies on CO diffusion through construction materials and building components. Initial small-scale experiments showed that concrete, brick, wood, and gypsum boards all exhibit very high permeability to CO [44]. The penetration time was found to depend strongly on the material type, the CO concentration gradient, and the material thickness. Figure 36 shows the breakthrough times (i.e., the time it takes to reach 1/10 of the reference CO concentration on the opposite side) under different concentration levels.

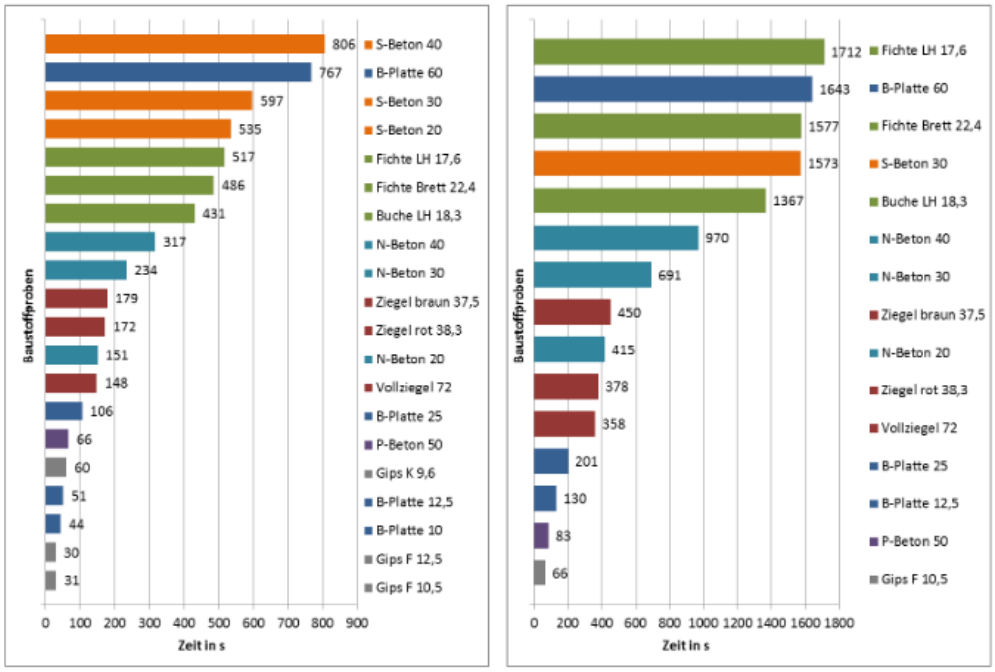


Figure 36 Breakthrough times (mean values) of the tested building material samples when exposed to a CO concentration of 1,000 ppm (left) or 10,000 ppm (right) [44]

It was found that gypsum boards exhibited the highest permeability to carbon monoxide among all tested materials. However, since the initial experiment used a relatively small apparatus, the investigations were extended to complete wall assemblies. Tests were conducted on wall elements sized 48 cm × 48 cm, as well as large-scale building tests. In medium-scale tests, both drywall and timber-frame walls (flat sections) and construction joints (rigid/sliding) were examined. Gypsum plasterboards exhibited significantly higher permeability than OSB boards. The breakthrough time—defined as the time until 1/10 of the reference CO concentration appeared on the opposite side—was about one hour for gypsum board walls [45]. Other studies also found the high permeability of gypsum boards [46].

The impact of carbon monoxide (CO) release from smouldering processes has been examined in [47]. Reported CO yields from smouldering fires in enclosed environments range between 0.1 and 0.25 g CO per gram of fuel consumed [48]. Consistent with these findings, experiments conducted using a Controlled-Atmosphere Cone Calorimeter showed that smouldering bio-based insulation materials produced CO yields between 0.1 and 0.3 g/g, depending on the ambient oxygen concentration [49]. These values indicate that the CO production of bio-based insulation during smouldering is within the range observed for other smouldering fuel types. According to [50], smouldering and thermal decomposition of bio-based insulation materials can generate a wide range of other gaseous products, including carbohydrates, aldehydes and ketones, carboxylic acids and esters, substituted phenols, furans, aliphatic hydrocarbons, substituted benzenes, and polycyclic aromatic hydrocarbons. Despite this complex emission profile, bio-based insulation materials exhibited a comparatively more favourable behaviour than conventional products such as polystyrene.

Both sustained smouldering and high material permeability may facilitate the migration of CO into adjacent occupied compartments, creating a potential life-safety hazard. However, it should be noted that smouldering in bio-based insulation materials generally occurs at relatively low mass-loss and heat-release rates. To date, investigations of CO emissions associated with cavity fires have largely been limited to laboratory-scale studies, and data from full-scale scenarios remain scarce.

Due to the limited research, it is currently not possible to provide a conclusive assessment of the risks of CO release from bio-based insulation during smouldering fires in concealed spaces

3.3.4. Firefighting implications

The following section presents selected firefighting implications associated with bio-based insulation materials, partly in combination with modern building systems such as photovoltaic installations. While each incident is unique, these (worst-case) examples illustrate critical challenges related to smouldering, hidden fire spread, and prolonged post-fire risks.

An incident in Emmaboda, Sweden (2025) involved a fire in a three-storey multi-family residential building, initiated on a balcony and rapidly spreading into the façade and roof structure (see Figure 37). The building featured a flat roof with layered construction, including mineral wool and wood fibre insulation, a ventilated cavity, and a photovoltaic (PV) installation. After the initial suppression of the fully developed balcony and apartment fire, the fire spread into the eaves and then into the roof structure, where it became established within concealed spaces [51].

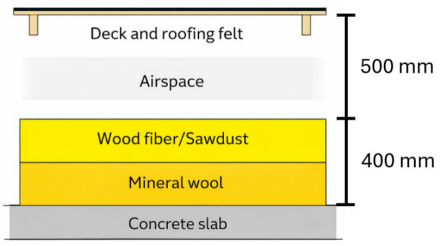


Figure 37 Visualisation of the roof construction according to [51]

Despite extensive firefighting efforts, including internal and external attack, ventilation, and eventual removal of roof sections and PV panels, the fire proved difficult to fully extinguish due to its propagation within the construction. The presence of PV systems further complicated operations, delaying tactical interventions such as cutting, extinguishing and requiring adjusted safety measures.



Figur 1. 2025-07-04 kl. 00:08 Figur 2. 2025-07-04 kl. 00:09

Figure 38 View of the balcony of the apartment where the fire broke out and the point where the fire spread to the roof area [51]

A defining characteristic of the incident was the development of persistent smouldering within the insulation and structural layers, particularly in the wood fibre and timber components. Following the initial intervention, the fire appeared to be under control, and no hotspots were detected during final checks using thermal imaging. However, within hours, renewed smoke and later flaming combustion were observed, leading to multiple re-ignition events over several days (five separate emergency responses). These secondary incidents were consistently associated with hidden smouldering processes within the roof and insulation layers, which had not been fully extinguished during earlier phases [51].



Figure 39 Overview of the extent of damage to the roof [51]

The incident highlights the inherent difficulty of detecting smouldering combustion in insulated and concealed constructions. Thermal imaging proved insufficient to reliably identify ongoing internal degradation, as the insulating materials limited surface temperature indications. Second, the incident demonstrates the long duration and delayed risk of smouldering, requiring an extended operational commitment far beyond the initial fire suppression phase.

The second analysis examines a fire incident at a detached house in Munich (Germany), in which the fire behaviour of a combustible insulation material (wood fibre insulation) was a key factor contributing to operationally challenging firefighting conditions. On 7 January 2024, a residential fire was reported at around 11.05 pm. When the first emergency services arrived, the fire was already well advanced, with open flames spreading from the kitchen area on the ground floor to the upper floor. The building was constructed using solid timber and insulated primarily with wood fibre. The building was occupied at the time of the fire; however, the occupants escaped to safety unaided.

Comprehensive firefighting measures were initiated immediately upon the fire brigade's arrival. In total, several fire hoses were deployed simultaneously, including two C-hoses and one B-hose for the interior attack, as well as additional C-hoses for external firefighting. Due to the rapid spread of the fire, the entire ground floor and large parts of the upper floor were affected, necessitating parallel firefighting operations across several operational sectors. Particularly challenging in this case was the fire behaviour of the wood fibre insulation installed within the timber stud or solid timber structure. Once the open flames had been extinguished, it became apparent that the fire had spread into the insulation layer and into the cavities of the structural elements.

The insulation materials exhibited pronounced smouldering behaviour, leading to repeated formation of hidden cavity fires. These were not initially visible from the outside but repeatedly re-ignited the flames when air entered during firefighting operations. Consequently, extensive and time-consuming opening of building components was required. Large sections of the façade and interior wall structures had to be opened with rescue saws to expose the embers within the insulation and extinguish them effectively, see Figure 40. Despite intensive firefighting efforts, new fires repeatedly broke out in the wood fibre insulation, complicating and prolonging follow-up extinguishing work.



Figure 40: Photos from the fire in Munich, followed by extensive firefighting operations [52]

The main firefighting operation extended over approximately 21 hours. Despite completion of the primary suppression phase, recurring smouldering and localized re-ignitions within the structure necessitated repeated follow-up interventions. Between the 8th and 20th of January 2024, an additional ten operations were conducted, totaling approximately 10 hours. Final overhaul and mop-up activities continued for nearly two weeks after the initial fire event. A total of 121 firefighters were deployed during the main operation, with a further 96 personnel involved in subsequent interventions. At least 88 self-contained breathing apparatus (SCBA) units were used, supported by six thermal imaging cameras to identify concealed hotspots. However, even with modern detection technologies, the complete localisation of smouldering zones within the insulated construction proved to be only partially achievable [52].

Smouldering fires in concealed spaces can pose significant operational challenges for fire and rescue services which highlights the need for improved techniques and tactics

This incident illustrates the significant operational challenges posed by fires in buildings containing combustible insulation materials derived from renewable resources. It highlights the persistence and detectability issues of smouldering combustion in concealed spaces, which are highly relevant for firefighting practice in contemporary timber-based construction.

4. FLAMING COMBUSTION

4.1. Introduction

Flaming combustion is defined as *combustion in the gaseous phase, often accompanied by light emission* [53].

Under certain conditions, smouldering combustion can transition to flaming combustion. The transition may occur if the smouldering region gains access to additional oxygen at the surface of the material, which can allow a flammable gas mixture to form. This chapter describes the process and risks associated with flaming combustion of bio-based insulation materials. In this context, the primary relevance of flaming combustion is if the bio-based material is not covered or plastered, and therefore, the surface of the material may be directly exposed to air and external heat.

This situation could be present if the application does not require fire protection (e.g. when acoustic insulation lining is used on the interior, or a reed thatch façade example in section 4.3) or if the protective layer (board or plaster) degrades due to heat impact, uncovering the insulation layer. The scenario of direct flame exposure and subsequent ignition and flaming combustion is essentially considered in standard European reaction-to-fire testing and classification.

The consequences of the ignition can be grouped based on the location of the ignition. If ignition occurs externally, the burning will contribute to the fire growth on the building envelope and potentially to fire spread between the compartments through windows. It will also hinder the evacuation and firefighting activities due to increased smoke and heat. If ignition occurs internally to the building, its fuel load will contribute to the compartment fire growth and should be considered as a permanent fuel load.

Bio-based charring materials may experience flaming extinction (or 'flameout') if a sufficient external heat exposure is not maintained, because the formation of a char layer insulates the underlying virgin material. When this occurs without external intervention (e.g. without application of water during firefighting), it is known as flaming 'self-extinction' or 'self-extinguishment'. Flameout can also result from external suppression efforts, including firefighting activities.

However, even when surface flame spread is suppressed, smouldering combustion can continue within the material's interior, slowly decomposing it in all directions. When the smouldering front eventually reaches the surface or edges of the material and encounters sufficient oxygen, it can re-ignite and transition back to flaming combustion. The transition from smouldering to flaming combustion is discussed in section 4.3.3.

Hazards associated with flaming combustion include the generation of heat, smoke and toxic and asphyxiant gases. The fire growth due to flaming combustion is significantly faster compared to smouldering combustion. Flaming combustion will lead to untenable conditions significantly faster than those created by smouldering combustion. Therefore, flaming combustion has typically been considered as the main risk during fire spread and fully developed fire phases. Consequently, many of the current testing and classification methods focus on the risks associated with flaming combustion. Smouldering can lead to the re-emergence of flaming combustion at the same or a different location after a prolonged period. Figure 41 illustrates this process.

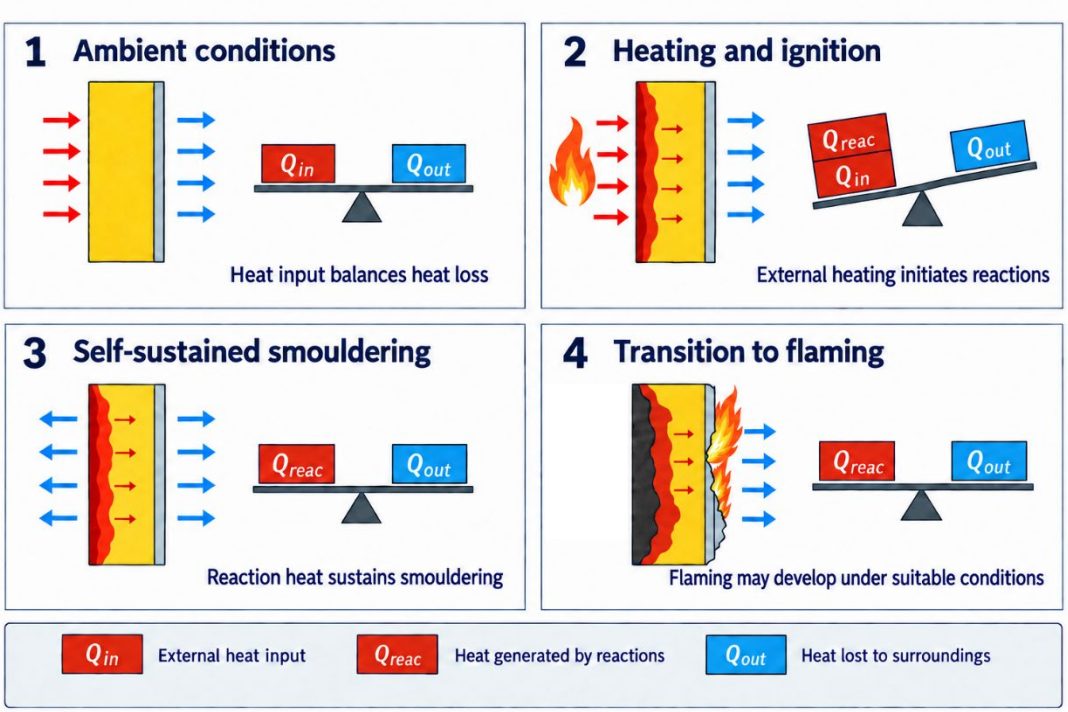


Figure 41: Simplified illustration of heating, ignition, self-sustained smouldering and possible transition to flaming in bio-based insulation. Q_{in} denotes external heat input, Q_{reac} heat generated by reactions, and Q_{out} heat lost to the surroundings. Smouldering can continue after external heating ceases if reaction heat sustains the process. Under suitable conditions, smouldering may transition to flaming.

Subfigure 1 shows the material under ambient conditions. Subfigure 2 illustrates heating and ignition by an external heat source. Subfigure 3 shows self-sustained smouldering, which can persist within the porous insulation after the external heat source has been removed. If oxidation generates sufficient heat to offset heat losses and heat adjacent material, smouldering can propagate through the insulation. Finally, subfigure 4 illustrates a possible transition to flaming when combustible gases released during thermal decomposition encounter sufficient oxygen and suitable ignition conditions.

4.2. Flame spread mechanisms

The aim of this section is to give a basic overview of flame spread, present the basic equations and highlight some of the important factors that can affect it. It is not the intention to cover all aspects and theories of flame spread, but rather to highlight the basics as relevant to bio-based insulation.

Flame spread in this context can be described as an advancing ignition front across the surface of a material. Following the initial localised ignition, heat from the flame (and any other external source) is transferred to the nearby material through radiation, convection, and conduction through the material itself. This raises the temperature of the nearby material, which then undergoes pyrolysis, releasing volatile gases that can be ignited by the flame. Combustion of this additional fuel, in turn, heats more of the unburnt material ahead of the flame, promoting further pyrolysis and moving the flame front onward.

The flame front may spread in the direction of the air flow (concurrent flame spread) or opposed to the entrained air. Concurrent spread is usually the case for upward flame spread (due to natural buoyancy of hot gases), whereas downward flame spread is usually opposed. Horizontal spread tends to be a combination of

both concurrent and opposed. Externally imposed air flows (e.g., due to wind) may induce either condition. Concurrent flame spread typically results in substantially faster spread rates than opposed spread, due to enhanced heat feedback from the flame and hot gases that are inclined towards the unburnt fuel in the direction of flow, leading to greater pre-heating that accelerates the ignition process.

Flame spread in its basic mathematical form is a velocity function (V_f), and can be defined as the change in distance, area (dA_b) or volume (depending on the dimension of the spread) of the burning region over the perimeter of the burning area (p) (none in 1D) and the change in time (dt).

$$V_f = \frac{dA_b}{p \cdot dt}$$

Translated into physical properties, the flame spread rate is governed by the ratio of heat transfer to the fuel and the thermal response of the fuel:

$$V_f = \frac{\dot{q}_f''^2 \cdot L_p}{k_f \rho_f c_f (T_{ign} - T_\infty)^2} \sim \frac{net\ heat\ transfer\ to\ the\ fuel}{thermal\ response\ of\ the\ fuel}$$

Where $\dot{q}_f''$ is the effective heat flux from the fire and L_p is the pre-heating region. k_f, ρ_f, c_f are the conductivity, density and specific heat of the fuel and $T_{ign} - T_\infty$ represent the difference between the ignition and ambient temperatures. This is still a simplified description of flame spread, as there are many factors that can impact flame spread across a surface.

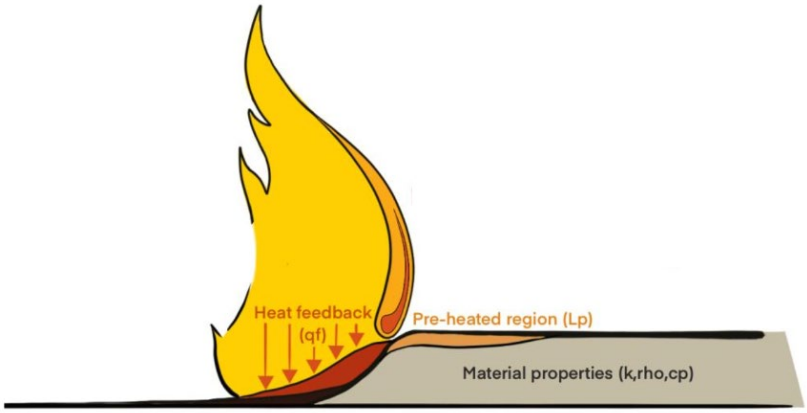


Figure 42: Visualisation of the basic flame-spread mechanism on the material surface (reproduced with permission [54])

4.3. Practical studies

The burning behaviour is characterised by its ignition properties (critical heat flux for ignition, ignition temperature, time to ignition in various conditions) and burning properties (heat of combustion, peak and average heat release rate, total heat release). The test methods can be grouped into micro-scale, small-scale (also called bench-scale), intermediate-scale, and large-scale tests.

Microscale tests are typically used to assess fundamental material properties and measure the related parameters. Most tests require grinding the samples, hence expelling the effects caused by the materials' morphology. Due to the small sample size, it theoretically excludes the effects of heat transfer and mass transport through the material's structure. Micro-scale tests include, but are not limited to, bomb calorimeter, thermogravimetric analysis, and differential scanning calorimetry.

Small-scale tests use larger samples, typically 10 cm in size. The effects of heat and mass transfer are included, as well as those of gas-phase combustion (i.e., radiation from the flame, air access). Small-scale tests include, but are not limited to, the cone calorimeter.

Intermediate-scale tests use a sample with characteristic dimensions of 1 m. Intermediate-scale tests may examine semi-complete systems, in which a combination of materials is investigated. These tests include local heating and heat and mass transport in all directions. At this scale, it is unpractical to evaluate fundamental material properties as there are too many variables, hence becoming system scenario-based tests for classification or demonstration purposes. Intermediate-scale tests include but are not limited to SBI and ISO 13785-1 small-scale façade test.

Large-scale tests use semi-complete systems with characteristic dimensions of several meters. Large-scale tests allow testing against fire impact that is more severe than intermediate-scale tests, which could be considered similar to what is expected in a realistic fire. Large-scale tests include, but are not limited to, large-scale façade tests and standard fire resistance tests. Despite the comparably large dimensions for fire tests, the specimens used in these tests are nevertheless only down-scale mock-ups of a full construction system as used in construction.

4.3.1. Material characterisation in micro- and small-scale tests

The gross heat of combustion for bio-based materials ranges from 12.7 kJ/g for magazine paper to 26.1 kJ/g for cork, as presented in Table 3.

Table 3: Heat of combustion of various bio-based materials based on [55]

Material	Gross Heat of Combustion [kJ/g]
Cork	26.1
Cotton	16.5 – 20.4
Paper—brown	16.3 – 17.9
Paper—magazine	12.7
Paper—newsprint /newspaper	19.7
Straw	15.6
Wheat straw	15.0
Spruce	21.8
White pine	19.2

The summary of fire properties retrieved from the cone calorimeter tests is presented in Table 4. The critical heat fluxes for ignition of raw materials used for bio-based building insulation range from 10 kW/m^2 for paper newsprint [55] to 15 kW/m^2 for cellulose [55], reed canary grass [56] and miscanthus [56].

Table 4 Fire-related parameters retrieved from cone calorimeter tests and respective exposure level for various bio-based materials tested in various forms. The data presented is generic and may not be representative for commercial products with different composition and densities.

Material	Effective heat of combustion [kJ/g]	Peak HRR per unit area [kW/m^2]	Average HRR per unit area [kW/m^2]	Time to ignition [s]	Specimen description	Ref.
Wheat straw	10.14 – 11.61 @ 50 kW/m^2	171.42 – 177.41 @ 50 kW/m^2	60.74 – 73.21 @ 50 kW/m^2	6 – 8 @ 50 kW/m^2	Density 75 – 175 kg/m^3. No fire retardants or additives.	[57]
Wood fibre insulation	11.84 – 12.53 @ 50 kW/m^2	224.91 – 254.14 @ 50 kW/m^2	104.49 – 104.56 @ 50 kW/m^2	6 @ 50 kW/m^2	Density 184 – 226 kg/m^3. No fire retardants.	[57] [58]
Cellulose fibres		144 @ 35 kW/m^2	91.2 @ 35 kW/m^2	50 @ 35 kW/m^2	Natural fibres Arbocel BC1000, from J. Rettenmeier & Söhne GMBH	[59]
Hemp shives	11.7 @ 35 kW/m^2 14.9 @ 50 kW/m^2	189.3 @ 35 kW/m^2 225.1 @ 50 kW/m^2		11.2 @ 35 kW/m^2 8.4 @ 50 kW/m^2	Shives from Afrimat Hemp, South Africa. No density or presence of fire retardants specified	[60]
Hemp fibres		114 @ 35 kW/m^2	58.1 @ 35 kW/m^2	9 @ 35 kW/m^2	Natural fibres from Chanvrière de l'Aube	[59]
Flax fibres		112 @ 35 kW/m^2	60.5 @ 35 kW/m^2	16 @ 35 kW/m^2	Natural fibres Fibras-S6B, from FRD	[59]
Sugar cane fibres		143 @ 35 kW/m^2	81.8 @ 35 kW/m^2	13 @ 35 kW/m^2	Natural fibres from Centro Universitario Fundaçao Santo André	[59]
Bamboo fibres		155 @ 35 kW/m^2	88.7 @ 35 kW/m^2	13 @ 35 kW/m^2	Natural fibres grade 3 from Bamboo Fibers Technology	[59]
Wood shavings and wood-concrete composite	7.5 @ 50 kW/m^2	79.4 @ 50 kW/m^2	55.5 @ 50 kW/m^2	14 @ 50 kW/m^2	Density 131.96 kg/m^3. Blend of species: Manilkara salzmanni, Erisma uncinatum warm, Cedrela fissilis, and Hymenolobium petraeum.	[61]

4.3.2. Intermediate and large-scale demonstration tests

Typical fire class for the different bio-based insulation materials is D or E. Reaction to fire performance class E has been reported for straw [62], [63] including compressed straw [64] and compressed straw bales [65] (refer to sub-section 2.1.1). Reed thatch also reaches class E, although application of a fire retardant impregnation may allow improving the reaction to fire class to C [66].

Intermediate- and large-scale demonstration tests typically involve a mock-up of a construction element or product that consists of several material layers rather than a single material. While testing a complete construction element/product allows for assessment by including the advantages of material interactions, these tests are prone to greater uncertainties and the influence of factors difficult to quantify (i.e., construction quality).

Cavity wall thermal and acoustic insulation materials are typically covered with rigid boards or plaster to ensure their protection against mechanical damage and moisture, to increase their thermal performance as well as to ensure a stable surface for the interior and exterior finish. As such, flame spread is rarely observed on the insulation materials themselves in intermediate and large-scale tests, although it may happen if the covering material is damaged. Reaction-to-fire classification may be required for cavity wall insulation to comply with building regulations in several countries. As stated earlier, bio-based materials typically reach reaction to fire class E.

Acoustic panels mounted on the interior walls or ceiling for sound absorption, damping, or scattering may be directly exposed to flames. In this document, reed thatch, used on roofs or facades, will also be considered an insulation material due to the air-filled structure that ensures good thermal and acoustic properties.

A case example of an intermediate scale testing programme of bio-based materials includes a test programme conducted at DBI on various thatch (reed) elements as part of the project *Det biogene montagebyggeri – konstruktion, brand og arkitektur* [67]. The project was carried out in collaboration with the Royal Danish Academy and funded by *Miljøteknologisk Udviklings- og Demonstrationsprogram (*MUDP). In 3 tests, focusing on different thatching method, and presented here, the fire exposure was ensured by gas burner at the bottom of the construction releasing either 50 kW or 100 kW (see Figure 43).

(a) Construction 1.	(b) Construction 2.	(c) Construction 3.
Compressed reed thatch layer of 180 mm thickness. 3 elements separated with vertically oriented joints protected by wood and cork	Thin layer of short / cut straw. The approximate thickness of straw is 2 cm.	Reed thatch (200 mm thickness) with applied clay in between the straw and excess clay removed from the surface.



Figure 43: Three tested constructions and early test flame spread

Photos of the constructions before the tests and during the early stages of the tests are presented in Figure 43. HRR and CO concentrations of the three tests are presented in Figure 44. The test results indicate early ignition and rapid surface fire spread for constructions unprotected by a clay layer (i.e., constructions 1 and 2). As a result, the peak HRR of these constructions is observed at the early stages of testing, and rapid flame spread is expected over the entire wall unless limited by physical obstructions, active fire suppression, or other fire protective measures.

After the drop in the initial HRR peak, the HRR increases steadily for the constructions with higher thickness (i.e., constructions 1 and 3). Furthermore, an increase in CO concentration measurements in the exhaust duct is observed. Both observations indicate the ongoing smouldering combustion inside the deeper layers of thatch. Eventually, the HRR for construction 1 increased sharply again at minute 55 due to the transition from smouldering to flaming combustion.

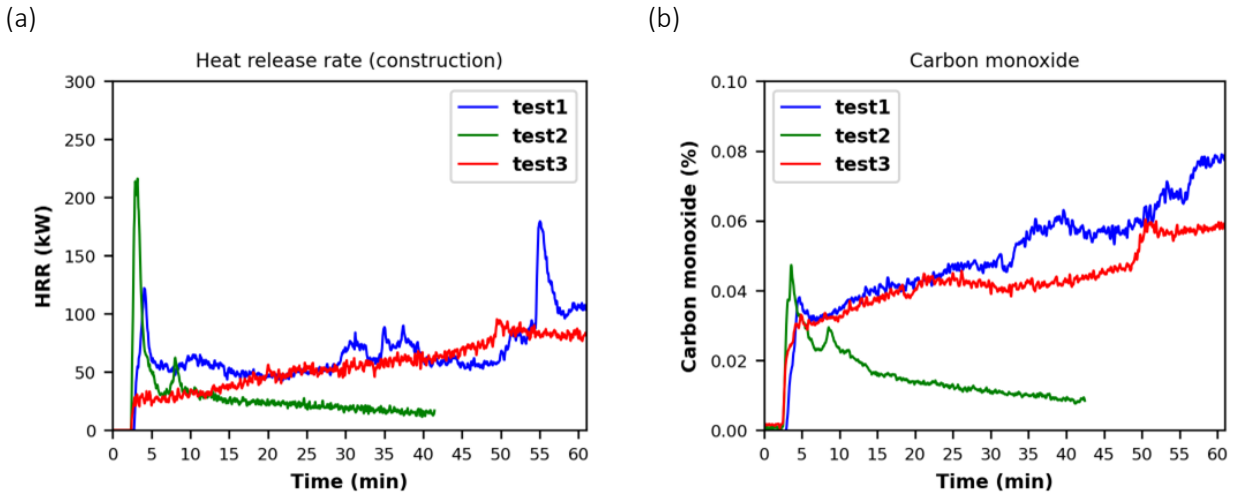


Figure 44: Measurements of 3 tests on thatch façade elements. Test 2 and 3 exposed to a larger burner (100 kW burner), Test 1 exposed to a 50 kW burner) (a) Heat release rate. (b) Carbon monoxide

4.3.3. Transition to flaming

Under certain boundary conditions, smouldering fires can transition to flaming combustion. In furnace tests conducted with 1 m × 1 m timber-frame elements, such a smouldering-to-flaming transition was observed after the fire-protective lining on the unexposed side failed due to thermally induced damage. The test specimens consisted of timber-frame panels measuring 1050 mm × 1050 mm × 160 mm, filled with commercially available loose-fill wood-fibre insulation composed of softwood fibres with flame-retardant additives. The experimental objective was to initiate smouldering under controlled and limited fire exposure.

The fire-exposed side was protected with a 12.5 mm fire-rated gypsum board (Type GKF) and subjected to the standard ISO 834 fire curve for approximately 15 minutes. Heating was terminated once the temperature at the insulation surface on the fire-exposed side reached at least 250 °C. The unexposed side was clad with a 16 mm medium-density fibreboard (MDF) panel. Following the heating phase, the specimens were removed from the furnace and positioned in pairs for a 24-hour observation period. A separating partition prevented thermal or gaseous interaction between the panels. Surface and internal temperatures were monitored on both sides of the specimens using thermocouples and infrared imaging.

Approximately six hours after removal from the furnace, a transition from smouldering to flaming combustion occurred (see Figure 45). The transition was attributed to the accumulation of pyrolysis gases within the panel, progressive internal heat buildup, and a sudden increase in oxygen availability following damage to the unexposed side of the cladding. Beyond local lining failure, progressive damage from concealed smouldering may create connected flow paths through a construction. Where these paths connect openings at different heights, buoyancy-driven airflow may increase the oxygen supply and favour a transition to flaming. The significance of this mechanism depends on the construction geometry and ventilation conditions.

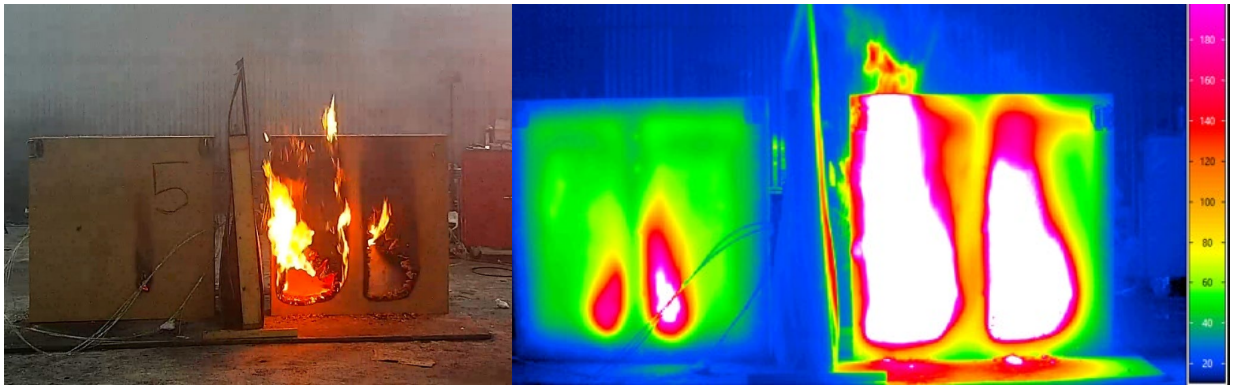
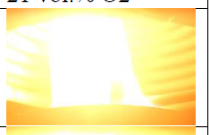


Figure 45: 24-hour fire tests with two timber frame components with transition from smouldering to flaming fire after 6 hours, CCTV (left) and thermal imaging (right) [68]

Small-scale experiments in a cone calorimeter with a controlled gas atmosphere [69] indicate that both the heat flux induced by smouldering and the local oxygen concentration have a significant impact on the conditions that trigger the transition from smouldering to flaming combustion, see Table 5.

Table 5: Visual observations of the test at the time of ignition in a controlled-atmosphere cone calorimeter using wood fibre insulation at different oxygen and heat flux levels [69]

Heat flux	13-14 vol.% O2	15-16 vol.% O2	17-18 vol.% O2	21 vol.% O2
30 kW/m²		N/A	N/A	
20 kW/m²			N/A	
15 kW/m²	No ignition			
10 kW/m²	No ignition	No ignition		

These transitions to flaming combustion may influence firefighting strategies. However, due to the limited available studies, it is currently not possible to conclusively assess the effects of this transition under realistic installation conditions.

Smouldering can persist after visible flames have ceased and may transition to flaming hours later if suitable thermal and ventilation conditions develop.

5. MITIGATION AND DESIGN STRATEGIES

The following chapter outlines general mitigation and design strategies intended to support fire safety professionals in addressing smouldering risks associated with bio-based insulation materials. Due to the complexity of building design, this document cannot provide universal solutions. Fire safety measures must always be considered alongside other performance requirements, including moisture transport, acoustic performance, structural design, durability, and constructability. Consequently, this chapter does not present a catalogue of pre-approved or prescriptive construction solutions. In addition, functional and regulatory requirements vary significantly between countries and jurisdictions, further limiting the applicability of standardised design examples. In addition to building code requirements for life safety, property protection may also be relevant.

The mitigation and design strategies presented in this chapter are based on a step-by-step, performance-based framework intended to support practitioners in assessing and managing smouldering hazards associated with bio-based insulation materials. The assessment begins by considering whether the insulation is protected by a covering or, for example, used unprotected as acoustic insulation. Where no covering is present, the primary fire safety concern shifts toward flaming ignition, flame spread and smoke production, and the reaction-to-fire performance of the material becomes the governing criterion.

If the insulation is covered, its smouldering propensity must be evaluated. Where uncertainties exist or where smouldering cannot be reliably excluded, the framework promotes further investigation rather than immediate exclusion of the material. This may involve advanced smouldering tests that provide deeper insight into material behaviour under application-relevant conditions and support project-specific risk assessments. If the resulting risk is deemed unacceptable, targeted mitigation measures are applied. These measures are structured around three complementary strategies: (i) reducing the likelihood of smouldering initiation, (ii) limiting the potential consequences of smouldering within building components, and (iii) enabling effective firefighting operations.

In addition, fire safety during the construction phase must be considered, as temporary exposure conditions may differ significantly from those in the completed building. Independent of the assessment of smouldering risks, the fire resistance of construction systems must also be verified. This is traditionally achieved through large-scale fire-resistance tests; however, this chapter also introduces state-of-the-art calculation methods for assessing fire resistance within a performance-based design approach.

The principles presented herein are intended to inform and support performance-based fire safety design and project-specific risk assessment. Responsibility for the interpretation, adaptation, and implementation of these strategies lies solely with the responsible fire safety professional. No liability is assumed by the authors for the application of the concepts described in this chapter.

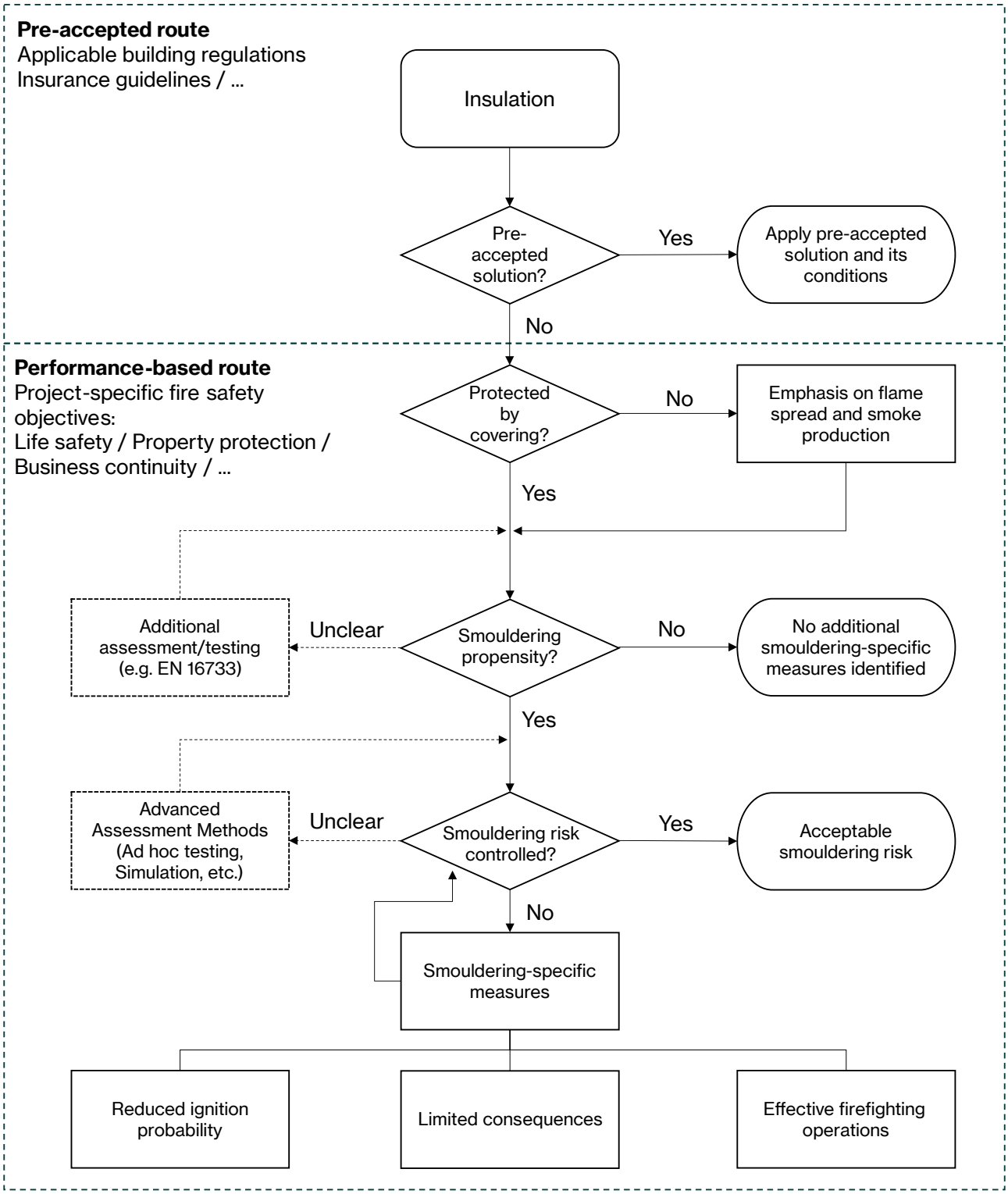


Figure 46: The decision pathway illustrates a performance-based approach to smouldering mitigation. The pre-accepted route applies where the intended construction and use fall within the scope and conditions of an applicable national pre-accepted solution. Otherwise, the proposed risk-informed assessment route may support application-specific documentation, subject to national requirements. The assessment draws on existing evidence and considers the intended application, with additional testing where necessary. The pathway is conceptual and does not constitute a standardised assessment or approval procedure. Fire safety during construction must be considered throughout.

Risk is commonly expressed as the product of the likelihood of an event and the severity of its consequences. In simplified form, this relationship can be expressed as:

$$R = h \times e$$

where **R** represents the overall fire risk, **h** denotes the likelihood (hazard frequency) of a given fire scenario, and **e** represents the consequences or effects should the scenario occur.

Fire safety risk assessment is inherently complex and may address multiple objectives simultaneously, such as safeguarding occupants, limiting property damage, or maintaining operational continuity. In practice, risk analyses are often qualitative and integrated into the overall fire safety concept. Comprehensive quantitative risk assessment is frequently impractical due to uncertainties in ignition probabilities, concealed fire development, and intervention effectiveness.

Semi-quantitative approaches can support structured comparison of alternative fire safety strategies. For example, the Fire Risk Index Method for Multi-storey Apartment Buildings (FRIM-MAB) was developed for the Nordic countries in [70] and later adapted in Germany (FRIM-MAB-D) [71]. Such index-based methods allow relative risk evaluation across different design options while maintaining methodological transparency. Steeger [4] further developed the FRIM-MAB-D and combined its application with an ecological assessment of fire protection measures in multi-storey timber buildings. The study developed model fire protection concepts for timber-frame construction incorporating combustible insulation in German building classes 4 and 5, explicitly considering the prevention of insulation smouldering as an additional protection objective. Within the assessment framework, these concepts were found to offer at least an equivalent level of fire safety to the regulatory benchmark, while also demonstrating the potential for lower CO_2 emissions.

The objective of a fire safety strategy is to ensure that fire-related risks remain within an accepted level of safety. Risk assessment is carried out in accordance with defined fire safety objectives, typically life safety or property protection. The first step is to identify relevant fire hazards and associated risk scenarios, including potential smouldering in concealed spaces.

To assess a material's propensity to smoulder, standard tests such as EN 16733 can be performed. Advanced smouldering tests can give additional information to quantify the likelihood of ignition and potential consequences, see section 5.6. If the risks associated with smouldering are demonstrated to be within the defined acceptance criteria for the relevant objectives, the assessment should be documented in the object-specific fire safety concept.

In other cases, the risks can be reduced through targeted fire safety measures that either decrease the likelihood of smouldering initiation or mitigate its consequences. Such measures may include:

- Preventing smouldering initiation (e.g. robust detailing, limiting ignition sources),
- Ensuring effective compartmentation of cavities to restrict concealed fire spread,
- Providing early detection and enabling prompt firefighting intervention.

The following sections build on this principle by presenting mitigation strategies to manage both likelihood and consequences across the most relevant smouldering and post-fire scenarios in buildings incorporating bio-based insulation materials.

5.1. Prevention or delay of smouldering

Preventing or delaying the smouldering ignition is a key objective in fire safety strategies for constructions incorporating bio-based or otherwise combustible insulation materials.

A material-level approach to mitigating flammability in bio-based insulation typically involves fire-retardant treatments. However, improved performance under flaming conditions does not necessarily imply reduced propensity to smoulder. Certain treatments promote earlier thermal decomposition and increased char formation while reducing the release of combustible volatiles. Although this can reduce flammability, increased char formation and prolonged oxidation may favour smouldering [72]. Further research is needed to establish how different treatments affect both flaming and smouldering behaviour under representative conditions. The development of treatments specifically targeting smouldering could provide a viable complementary approach. One example is the InnoDämm project (2019–2021), in which Fraunhofer WKI, ET Brandschutz and Gutex investigated smouldering-retardant formulations for wood-fibre insulation. The project combined modelling of the smouldering process with the development of additive mixtures, incorporating evaluation using a dedicated experimental apparatus and EN 16733.

Any claimed reduction in smouldering propensity should be verified through appropriate testing. However, demonstrating improved material performance does not automatically establish regulatory acceptance for a particular application. As discussed in Section 2, standardised documentation and acceptance routes for smouldering performance are not consistently established across the countries considered. Furthermore, reduced material-level propensity to smoulder does not, on its own, demonstrate the smouldering resistance of the complete construction. System-level measures, particularly continuous protective coverings and appropriate detailing, therefore remain important for preventing or delaying ignition of the insulation.

An extended protection time provides a larger operational window for firefighting intervention. If the insulation temperature can be maintained below critical smouldering thresholds during the early fire phase, the likelihood of a sustained smouldering process is significantly reduced. Even if smouldering is eventually initiated, delayed onset limits the depth of thermal degradation and reduces the risk of subsequent transition to flaming combustion.

A primary design measure to achieve delayed smouldering initiation is the use of protective coverings that thermally shield the underlying insulation. While nearly any continuous cladding provides some protection against direct flame impingement, the level and duration of protection vary substantially depending on material properties and system design. Combustible claddings, such as thin wood-based panels, may delay ignition only briefly, whereas non-combustible or limited-combustible boards with high specific heat capacity, low thermal conductivity, and dehydration effects (e.g., gypsum-based products) can significantly slow the rate of temperature rise in the insulation.

Table 6 provides an overview of different coverings based on the expected scenario. However, the effectiveness of protective coverings can be significantly compromised by service installations and penetrations. Electrical boxes, ventilation ducts, pipes, recessed luminaires, and similar installations may locally reduce the thermal barrier, create leakage paths for hot gases, or introduce thermal bridges that accelerate heat transfer into the insulation.

Table 6: Examples for different coverings and protection times (tested systems required for classification)

Ignition Protection	Indicative protection time	Example Coverings	Illustrative Fire Scenario
Low	≥ 10 min	12.5 mm Type F/Type A gypsum plasterboard or gypsum fibreboard 15 mm OSB/Chipboard/MDF 18 mm Plywood	Small ignition source (e.g. paper bin)
Medium	≥ 30 min	2 × 12.5 mm Type F gypsum plasterboard or gypsum fibreboard	Extended fire with early intervention
High	≥ 60 min	2 × 18 mm Type F gypsum plasterboard or gypsum fibreboard	Extended fire with delayed intervention

Indicative values based on EN 1995-1-2:2025 for insulation-backed wall linings under standard fire exposure, subject to the specified material properties and detailing requirements.

Poorly sealed joints and discontinuities at interfaces (e.g., wall-to-floor junctions or façade connections) may also permit hot gases to enter cavities and initiate concealed smouldering remote from the primary fire exposure. Accordingly, the design should ensure that:

- Penetrations are minimised and properly sealed using tested fire-stopping systems.
- Installation zones are planned to avoid direct exposure of combustible insulation.
- The continuity of protective layers is maintained across joints and interfaces.
- The fire performance of the assembly, including typical service installations, is considered in the assessment.
- The continuity of cavity insulation and protective coverings is maintained throughout the building's service life, accounting for potential settlement, displacement and gap formation.

In summary, increasing the protection time through robust, continuous protective coverings is an effective strategy to prevent or delay smouldering. Nevertheless, the protective function must be evaluated at the system level, with particular attention to penetrations and detailing, as local weaknesses can govern the overall fire performance and negate the intended delay effect.

5.2. Fire spread mitigation

5.2.1. Timber component connections

In timber construction, concealed cavities, such as façade cavities, service voids, and junction interfaces, serve as critical pathways for concealed fire spread. This risk is particularly pronounced at timber joint connections, including wall-to-floor interfaces, façade-to-frame junctions, and openings (e.g. windows), where geometric complexity and construction tolerances can compromise fire protection measures. Experimental investigations on timber component joints show that these interfaces inherently constitute potential fire and smoke transfer paths due to the presence of unavoidable gaps (element joints, component joints, and installation penetrations) [73]. Even when constructed in accordance with current standards, absolute smoke-tightness cannot be achieved in practice, as all joints exhibit a certain degree of permeability to gases and thermal flow. This is particularly relevant for smouldering processes, where low-intensity heat release and long-duration exposure increase the likelihood of unnoticed fire propagation through small leakage paths.

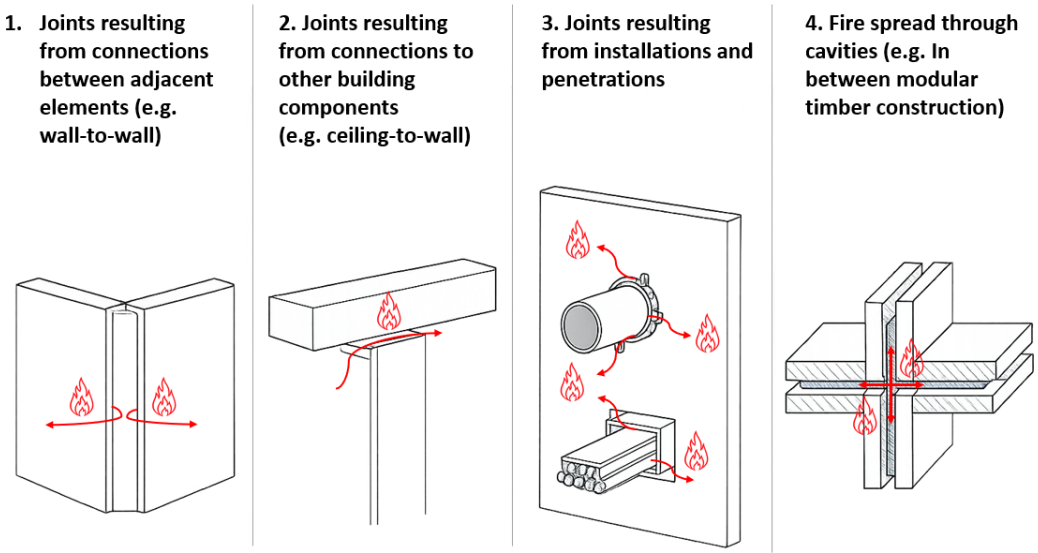


Figure 47: Schematic illustration of fire and smoke spread pathways through construction joints, cavities and penetrations.

From a fire dynamics perspective, timber joint connections facilitate concealed fire spread through two primary mechanisms: (i) convective transport of hot gases and pyrolysis products through leakage paths, and (ii) conductive heat transfer across discontinuities in protective layers. The report [73] identifies that continuous or aligned joints, such as uninterrupted vertical or horizontal cavities, are especially critical, as they can form extended pathways for fire spread if not adequately interrupted.

A key finding is that the fire performance of joints is governed less by the base structural system (e.g. mass timber vs. timber frame) and more by the detailing and execution of the joint itself. In particular, the resistance against fire spread depends on two coupled properties:

- Thermal resistance, determined by material selection, layer configuration, and geometric dimensions
- Resistance to airflow (smoke tightness), which governs the transport of hot gases through the joint.

Both properties must be maintained for the required duration of fire exposure to ensure adequate performance. Robust joint detailing is essential to mitigate fire spread at timber connections. Effective measures include:

- Implementation of continuous air-tight layers, which significantly reduces smoke and hot gas transport across joints;
- Use of non-combustible insulation materials (e.g. mineral wool) within joint cavities to limit heat transfer and delay ignition;
- Compression and proper installation of joint fillers, improving sealing performance and reducing leakage rates;
- Application of redundant protective measures on both sides of the joint, increasing robustness against local defects.

Similarly, installation-related penetrations must be carefully controlled, as they introduce additional leakage paths that can significantly increase the risk of concealed fire spread. A comprehensive guideline for timber connections has been published in [74] while fire stops in cavities have been investigated in [75].

5.2.2. Rear-ventilated facades

Rear-ventilated wood façades introduce a critical fire-spread pathway through the ventilation cavity, which can act as a chimney, significantly accelerating vertical and concealed fire propagation. A key mechanism is the spread of fire inside the cavity. This concealed fire spread is particularly critical because it can lead to rapid vertical fire propagation and subsequent ignition of upper façade sections.

To mitigate these risks, cavity compartmentation is essential. Fire barriers, in the form of cavity barriers combined with plume deflectors, have proven effective at suppressing fire spread in wood-clad facades [76]. The installation cassettes with non-combustible insulation between exterior walls with bio-based insulation can be useful to prevent a fire spread through the insulation, see Figure 48.

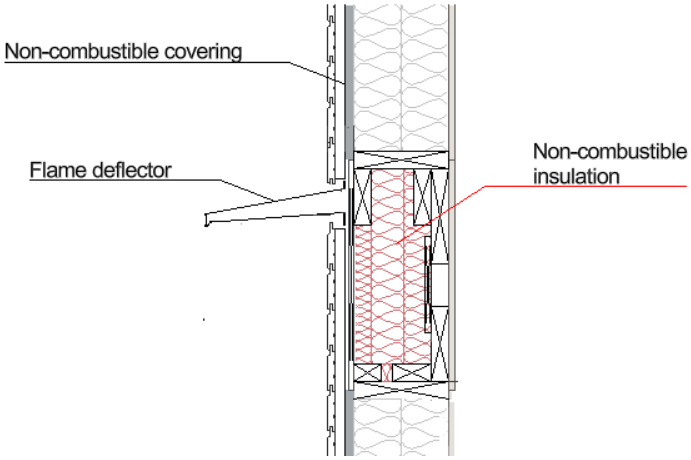


Figure 48: Mineral-wool barriers and flame deflector in a rear-ventilated wood-clad façade

Overall, effective fire spread mitigation in rear-ventilated façades requires a multi-layered approach that combines cavity barriers, plume deflectors, non-combustible materials, and robust detailing. These systems should be validated through performance-based design and large-scale testing.

5.2.3. External thermal insulation composite systems

Limiting fire spread in external thermal insulation composite systems (ETICS) is particularly important in multi-storey buildings with combustible insulation where smouldering ignition is expected and façade areas are difficult for fire service access. In this case, fire barriers represent an effective passive measure to restrict fire propagation by introducing non-combustible insulation zones within otherwise combustible façade systems, thereby interrupting both flaming and smouldering spread.

The study referenced in [31] demonstrated that, under the investigated test conditions, a stone wool fire barrier with a minimum height of 200 mm and a thickness equal to that of the adjacent bio-based insulation effectively prevented vertical fire spread; the barrier material should be classified at least A2–s1, d0 according to EN 13501-1 and should pass the smouldering combustion test in accordance with EN 16733.

The study suggests fire barriers around openings and in areas where smouldering initiation is expected to confine fire spread to façade zones accessible to firefighting operations, for example, around windows. For such targeted applications, a reduced barrier height of 100 mm was deemed sufficient [31]. However, the exact detailing must be determined based on the expected fire scenario, building configuration, national regulatory requirements, and system-specific approvals such as ETICS system certifications.

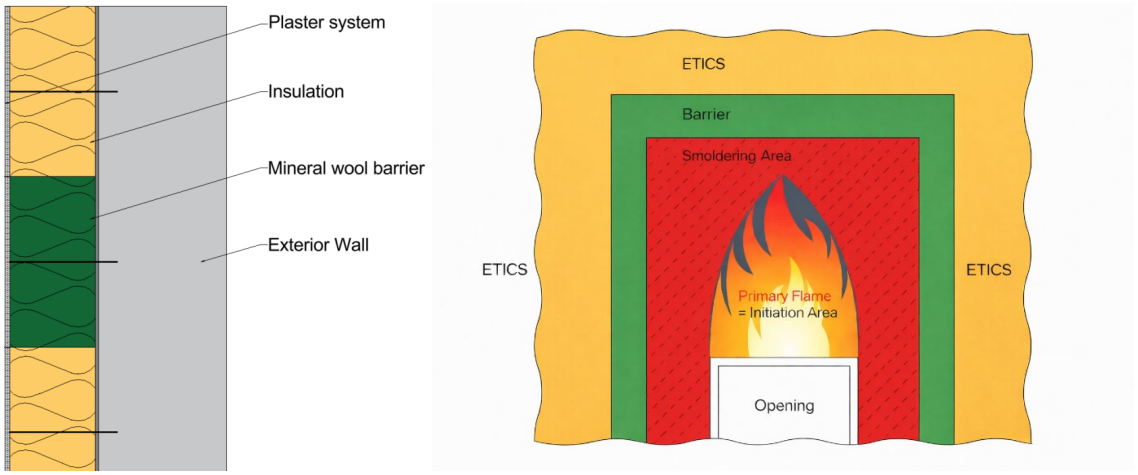


Figure 49: Principle sketch of an ETICS with mineral wool fire barrier, adapted from [31]

5.2.4. Steel-envelope systems

The use of non-combustible insulation as a smouldering barrier within bio-based insulation systems has also been shown to be effective in façades employing steel-envelope constructions [34]. In an intermediate-scale façade test, a system consisting primarily of wood-fibre insulation sandwich panels, with an integrated mineral wool sandwich panel, was investigated for fire spread. The inclusion of the non-combustible mineral wool element effectively interrupted the self-sustained fire propagation process.

These findings indicate that strategically placed non-combustible insulation layers can serve as effective fire and smouldering barriers within façade systems containing bio-based insulation. Similar to cavity barriers used to limit flame spread in ventilated façades, such barriers can compartmentalise large insulation fields and restrict the horizontal or vertical propagation of smouldering combustion. The effectiveness of this measure will depend on the continuity, thickness, and positioning of the non-combustible layer, as well as on the specific façade configuration and expected fire exposure.

While further research is required to establish design rules for different construction systems, the results suggest that hybrid insulation concepts combining bio-based and non-combustible insulation materials may offer a practical strategy for mitigating concealed fire spread while retaining many of the environmental benefits associated with bio-based insulation products.

5.3. Firefighting strategies

As repeatedly stated, the use of combustible insulation materials entails the risk that, in the event of a fire, these materials may ignite within structural assemblies and smoulder unnoticed. The results of the “HoBraTec” research project demonstrate that, for effective firefighting operations, the localisation of concealed fires, or their reliable exclusion, is of decisive importance.

Due to limited oxygen supply, incomplete combustion occurs, which, compared to flaming combustion, is characterised by lower combustion temperatures and significantly higher carbon monoxide (CO) emissions. Heat transfer from the seat of the fire to the component surface can take a comparatively long time, depending on the structural configuration, and this must be considered when interpreting surface temperature measurements.

5.3.1. Identification of cavity fires

Thermal imaging can support the detection of concealed smouldering, but it records surface temperatures rather than conditions within the construction. Interpretation must therefore account for heat transfer through the protective layers and airflow within cavities. Air currents may cool the inner surface of the cladding, masking the thermal signature of an underlying smouldering fire. Conversely, they may transport heat to other parts of the construction, producing elevated surface temperatures away from the actual fire location. Consequently, the absence of a detectable temperature rise does not rule out concealed smouldering, and a detected hot spot does not necessarily identify its location.

It should be noted that the measurement accuracy of thermal imaging cameras varies by model, which may influence the detection of concealed fires within assemblies. In addition, the application of extinguishing water may cause cooling effects at component surfaces, thereby negatively affecting the detectability of cavity fires by means of thermographic methods, as illustrated in Figure 50.

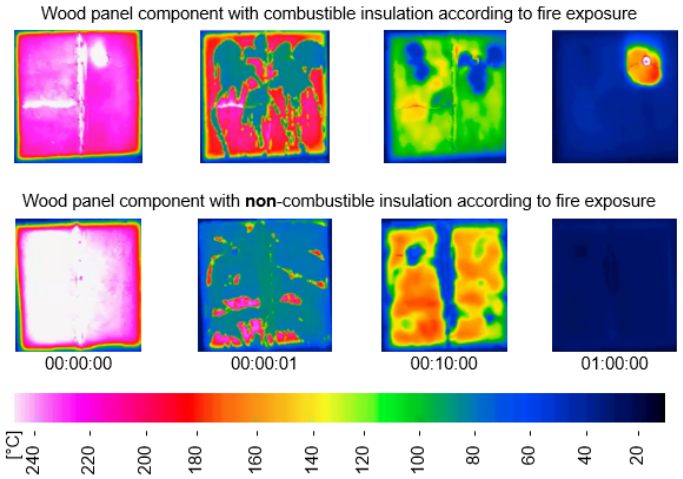


Figure 50: Thermal images of wooden panel components with and without combustible insulation after exposure to fire. Time step 1: immediately after exposure to fire; Time step 2: immediately after extinguishing the surface; Time step 3: 10 minutes later; Time step 4: 1 hour after exposure to fire

These factors may necessitate prolonged monitoring to identify temperature changes at component surfaces and draw appropriate conclusions. Nevertheless, thermal imaging cameras are essential for operational success, as they enable large-area inspection of component surfaces within a reasonable time frame. Due to carbon monoxide emissions from incomplete combustion processes, such as those expected in structural cavities, gas detection technology is a valuable complement to thermographic methods. Carbon monoxide (CO) is particularly suitable as an indicator gas, as it is released in significant quantities during incomplete combustion, and CO sensors are widely integrated into fire service gas detection and warning devices. Because CO can permeate construction materials commonly used in timber frame construction, detection is possible even at the component surface, thereby enabling localisation of the emission source [45]. However, individual layers may impede detection.

For building physics reasons, exterior wall assemblies are typically equipped with a vapour retarder or even a vapour barrier on the room-facing side. In such cases, measurement through the lining is only possible to a limited extent, as the membranes significantly hinder CO permeation. Targeted perforations (drilled openings) are therefore required to detect or exclude a CO-emitting source within cavities. Figure 51 illustrates a sequence of actions recommended by the HoBraTec project.

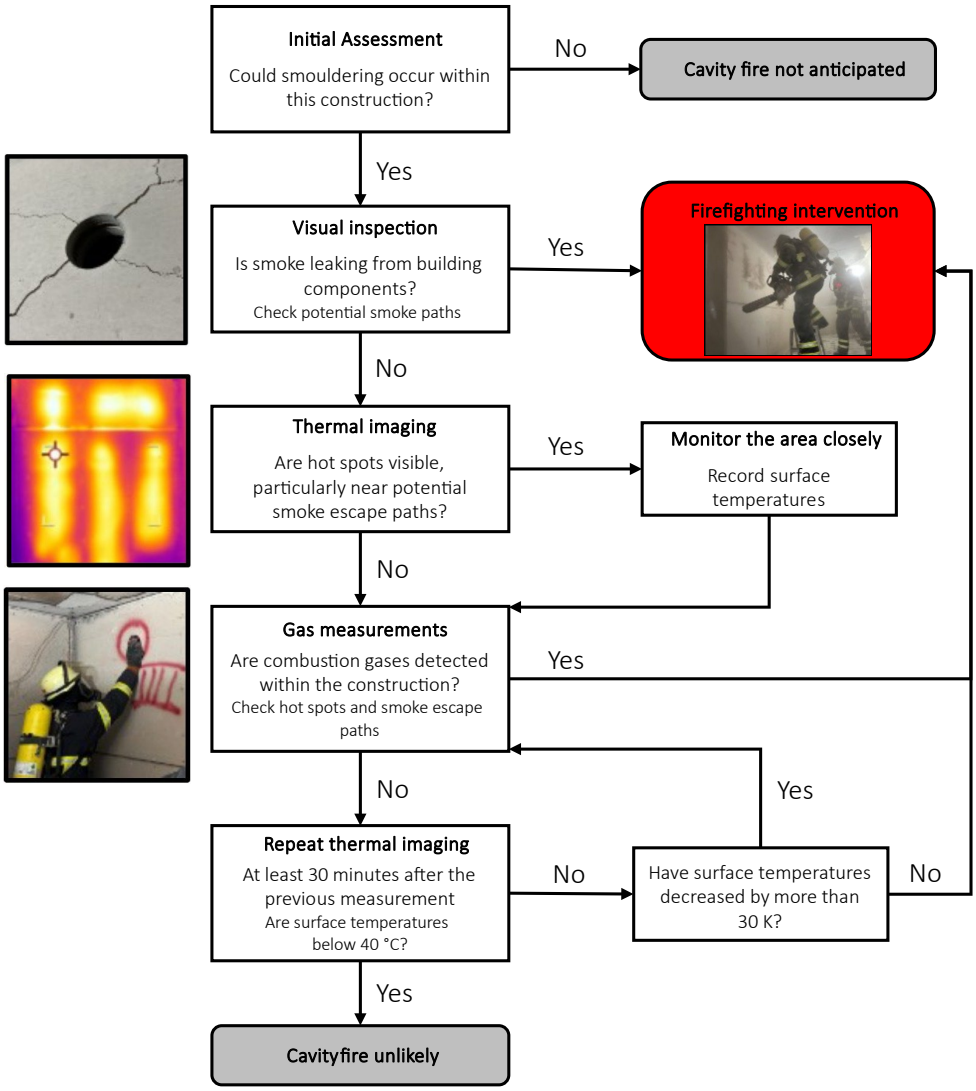


Figure 51: Flowchart for efficient cavity fire detection developed in the HoBraTec project

In addition to measurement-related challenges, fire services must also address structural challenges, as detailed knowledge of the building construction is fundamental to operational success. For example, if a compartment fire constitutes the initial incident, an assessment of the fire-exposed structural components must be conducted following extinguishment.

Construction details are generally not available on site, necessitating the application of probing methods. It must be determined whether the existing assemblies permit fire development within the structure, as this cannot be excluded in timber-frame constructions with combustible cavity insulation. Within the HoBraTec research project, endoscopic cameras yielded reliable results; however, their use requires experience.

Analysis of the fire dynamics of construction-related fires indicates that fire spread frequently occurs via installation elements (e.g., light switches, electrical outlets), as these interrupt the protective fire-resistant lining. Openings for switches, sockets, junction boxes, etc., therefore represent suitable starting points for structured investigation. Visible smoke emission at these weak points, or at cracks or other damage to the fire-protective lining, can be regarded as reliable evidence of a cavity fire (visual inspection). In general, multiple measurements at appropriate time intervals are required to reliably exclude fire within a structural assembly.



Figure 52: Application of an endoscopic camera by firefighters to identify wall construction

The seemingly straightforward approach of removing linings over large areas to exclude concealed fires may be proportionate in individual cases. Generally, however, this approach should be avoided, as severe structural damage may occur, particularly if load-bearing layers are dismantled. Moreover, such measures are highly personnel- and resource-intensive, as they must be carried out while wearing self-contained breathing apparatus (SCBAs) due to potential CO emissions from concealed fires. By applying the described detection strategy in a targeted manner, personnel and material requirements, as well as damage resulting from firefighting operations, can be kept to a minimum. The presented tactical approach was successfully applied in full-scale fire tests [26].

Currently, only a few fire services in Europe have standardised procedures for detecting cavity fires in timber structures. In the future, awareness of this issue must be raised, and relevant content must be incorporated into firefighters' training, including station-based training.

5.3.2. Firefighting methods for cavity fires

For façade systems, the feasibility of these interventions depends on whether firefighters can safely reach and open the affected construction. Building height, façade geometry, access and operating space for aerial appliances, and the configuration of protective layers should therefore be considered when developing the fire safety strategy. Reaching the façade surface does not necessarily provide access to smouldering insulation behind it.

Although fire and smouldering barriers may limit propagation, they do not, by themselves, ensure access for detection, extinguishment or removal of affected material. Where the strategy relies on fire-service intervention, the practicality of these operations should be discussed with the relevant fire service during design, including the limitations of available equipment and safe working positions

The literature describes various approaches for fighting cavity fires [77]. Opening fire-affected structural components is generally unavoidable and requires substantial personnel and material resources, as operations must be conducted while wearing SCBAs.

Once the assembly has been opened, the burning material can be removed, transported outside, and extinguished if necessary. This tactical approach is described in the literature [77] as highly labour-intensive, as limited detection capabilities often necessitate opening all potentially affected components. In the case of more complex cavity fires, it should also be borne in mind that opening up the structure at a point that has not yet been affected may create ventilation pathways that could negatively impact the cavity fire elsewhere.

The findings from the HoBraTec research project indicate that the required effort can be significantly reduced if careful fire detection is performed before opening structural components. Ideally, opening measures can be limited to a small number of cavities, thereby conserving personnel, technical, and time resources while also minimising damage. The cited literature considers the application of water via a piercing nozzle (extinguishing lance) to be an effective method. Water is injected directly into the structure to suppress the cavity fire and reduce the risk of a transition to flaming when the assembly is opened. However, experimental investigations conducted within the HoBraTec project demonstrated that the piercing nozzle must be applied above the cavity fire; otherwise, smouldering may continue above the injection point. Furthermore, the results showed that successful extinguishment cannot be guaranteed using this tactic alone. Consequently, the subsequent opening of the structural component remains indispensable afterwards.

The introduction of extinguishing agents into structural assemblies may be appropriate if immediate and targeted removal of the burning material is not feasible, for example, due to limited personnel or equipment resources. In general, however, the use of extinguishing agents should be kept to a minimum to reduce secondary damage. In this context, the use of wetting agents is recommended, as the reduced surface tension improves water penetration into the burning material. The use of firefighting foam is not recommended due to its poor penetration [78].

5.3.3. Tools for opening structural components

Effective fire suppression within structural assemblies requires efficient opening techniques. Within the HoBraTec research project, opening tests were therefore conducted on representative wall and ceiling assemblies. The investigation included both solid timber and timber-frame constructions with varying layer configurations. Installation cavities, suspended ceilings, and façade systems were considered, along with various types of insulation materials.

Tool selection was initially based on standard equipment carried on firefighting vehicles and was supplemented by tools commonly used in construction. The tested tools can be categorised into cutting tools and prying tools.

The use of prying tools proved consistently disadvantageous, as opening the target required considerable physical effort and time. Since operations must generally be performed while wearing an SCBA, this approach is not practical. Cutting tools, by contrast, enabled more precise and often more ergonomic operation. Chainsaws were identified as the preferred tool. Both gasoline-powered and battery-powered chainsaws achieved satisfactory results. Firefighters are typically well-trained in their use, which is a decisive success factor. The application of a cutting depth limiter can further enhance operator safety. Specialised chains are not required.

5.4. Fire safety during construction

Fire safety during construction and refurbishment is an important issue that requires explicit consideration alongside the fire performance of the completed building. Protective coverings, compartmentation and permanent fire protection systems may be incomplete or temporarily unavailable, while construction activities introduce additional ignition sources. Consequently, measures intended for the completed building cannot be assumed to provide equivalent protection throughout construction. The Swedish handbook *Brandsäkert byggnads- och anläggningsarbete* emphasises integrating fire safety into planning, design and execution, providing practical guidance, templates and checklists supporting SBF 505:2.

A project-specific Construction Phase Fire Safety Plan (CPFSP) is recommended, developed before construction begins and reviewed as the work progresses. This approach is described in the chapter *Fire Safety During Construction and Refurbishment* in the *SFPE Handbook of Fire Protection Engineering* [79]. The plan should establish responsibilities, identify fire hazards at the different construction stages, and document preventive measures and emergency arrangements. It should be proportionate to the project's risks and coordinated with applicable national requirements. Practical measures include controlling hot works and temporary electrical installations, safely storing combustible materials, removing combustible waste, and maintaining suitable fire warning, escape and firefighting arrangements. These measures should be communicated to contractors and reviewed when site conditions or work activities change.

For projects incorporating combustible bio-based insulation, this white paper recommends that the CPFSP explicitly address periods when insulation is exposed or protective coverings, penetrations and cavity barriers remain incomplete. Work sequencing and temporary precautions should limit exposure to ignition sources. Where smouldering is a credible hazard, the plan should also address potentially concealed ignition following hot works, including appropriate monitoring and follow-up inspection. These considerations apply general construction-phase fire safety principles to the materials and assemblies concerned; they do not constitute a separate standardised assessment method for smouldering.

5.5. Separating function method

Databases such as dataholz.eu and Brandbank.dk provide structured access to documented fire tests and verified fire-resistance classifications for timber and bio-based building components. These resources can serve as an initial basis for identifying existing fire resistance ratings and previously tested construction assemblies. Where comparable configurations are available, they support design decisions without the need for additional testing.

Calculation-based approaches for determining the fire resistance of constructions using bio-based insulation materials will be very important in the future. An example of this is the inclusion of the Component-Additive Method for bio-based insulation materials in Eurocode EN 1995-1-2:2025 [80].

The Component-Additive Method, originally introduced in Eurocode EN 1995-1-2:2004 and subsequently refined, provides a rational framework for calculating the fire resistance of timber-based separating elements. The method is based on the fundamental assumption that each individual layer within a building component contributes to the overall fire resistance. By summing these individual contributions, the fire resistance duration of a multi-layer timber component subjected to one-sided fire exposure can be determined, particularly with respect to the separating function defined by the integrity (E) and insulation (I) criteria.

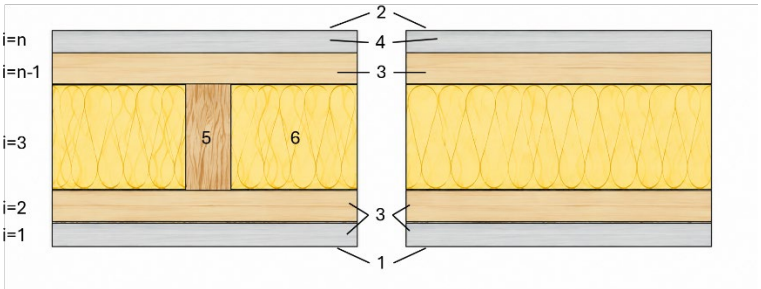


Figure 53: Component-Additive-Model in Eurocode 5, 1: Fire-exposed side, 2: Unexposed side, 3: Coverings as protective layers, 4: Last covering as insulation layer, 5: Structural timber, 6: Cavity (empty or filled with insulation material) as a protective layer, based on the principles in [81]

Within this framework, failure of the separating function occurs when either integrity or insulation on the unexposed side can no longer be maintained. For planar timber components such as walls and floors, the time during which the separating function (EI) is ensured is calculated as the sum of the protection times of all layers located on the fire-exposed side and the insulation time of the final layer facing away from the fire. Conceptually, this can be expressed as:

$$t_{ins} = \sum_{i=1}^{i=n-1} t_{prot,i} + t_{ins,n} \geq t_{req}$$

t_{ins} Time until separating function (EI) is guaranteed [min]
$t_{prot,i}$ Protection time of the layers up to the last layer facing away from the fire[min]
$t_{ins,n}$ Insulation time of the last layer facing away from the fire[min]

EN 1995-1-2:2025, Section 7.3 extends the applicability of the component-additive method to timber components exposed to the standard ISO 834 fire curve for durations of up to 120 minutes. It includes design approaches for a broad range of covering and protective materials, such as gypsum plasterboards, clay plasters, and wood-based panels. Importantly, bio-based insulation materials have been explicitly introduced into the method. At present, however, the new Eurocode provides material-specific design equations only for wood fibre insulation and cellulose insulation, reflecting the limited availability of validated experimental data for other bio-based products. The method conceptually distinguishes among the functional roles of component layers: fire-exposed coverings that serve as protective layers, cavities (either empty or filled with insulation) that contribute to thermal delay, and the final covering on the unexposed side that primarily acts as the insulation layer. Structural timber members may also be considered protective layers, depending on their position and exposure.

For materials and products not covered by the design equations in Clause 7 of EN 1995-1-2:2025, Annex G provides a procedure for deriving parameters for the Separating Function Method, which follows the component-additive principle. This offers a route for incorporating additional bio-based insulation products into calculated fire-resistance design, supported by product-specific fire testing and thermal modelling.
The procedure combines model-scale furnace tests, calibration of effective thermal properties, and verification against full-scale fire tests. The model-scale specimens should have fire-exposed dimensions of at least 450 mm × 450 mm and are tested horizontally with fire exposure from below, following EN 1363-1 with the modifications specified in Annex G. Testing must cover the minimum and maximum thicknesses and, where relevant, densities within the intended application range, with at least two specimens for each investigated parameter. Additional intermediate values are required where the insulation thickness range exceeds 100 mm or the density range exceeds 20 kg/m³.

The measured temperature histories are used to calibrate temperature-dependent effective thermal conductivity, specific heat and density. The simulations should reproduce the measured times to reach 150 °C and 300 °C within one minute. The calibrated properties are then used in prescribed simulation configurations to derive design equations for basic protection times and coefficients accounting for the position of the insulation within a layered construction. Joint effects are determined through additional testing where applicable. The resulting design equations must be verified against at least one full-scale fire test, normally on a horizontal furnace unless the product is used exclusively vertically. Suitable existing tests may be used, provided they support verification and cover the intended duration of application. The calculated protection time must not exceed that obtained experimentally. This procedure establishes parameters for assessing the separating function under standard fire exposure. It does not, by itself, demonstrate resistance to sustained smouldering.

5.6. Advanced assessment methods

5.6.1. Advanced smouldering tests

Advanced smouldering test methods aim to reproduce the fundamental mechanisms governing smouldering initiation and propagation (see Chapter 3) under controlled and reproducible conditions. Accordingly, such methods should account for well-defined airflow and heat-transfer conditions representative of realistic end-use scenarios. Furthermore, they should allow observation of self-sustained smouldering propagation initiated by a controlled, removable heat source that resembles realistic ignition conditions. Based on these requirements, it becomes evident that existing standardised methods, such as EN 16733, only partially capture the relevant smouldering mechanisms.

One example of such an advanced approach is the CASPR methodology. The Controlled-Atmosphere Smouldering Propagation Reactor (CASPR) was developed at DBI to investigate smouldering ignition and propagation in bio-based insulation materials under well-defined and reproducible boundary conditions. Unlike standardised reaction-to-fire or smouldering tests, CASPR is specifically designed to isolate and quantify the governing mechanisms of smouldering in porous insulation materials.

CASPR consists of a vertically oriented, insulated tube reactor that promotes predominantly one-dimensional, buoyancy-driven smouldering propagation, see Figure 54. Ignition is initiated by a controlled electrical heat source embedded at the base of the specimen, while the surrounding atmosphere is precisely regulated using independent air and nitrogen mass flow controllers. This allows systematic variation of oxygen availability and total flow rate, enabling the investigation of both oxidative and near-inert conditions. Radial heat losses are minimised through surrounding mineral insulation, ensuring well-defined axial heat transfer.

The experimental setup integrates continuous measurements of longitudinal temperature profiles, specimen mass loss, gas composition (O_2, CO_2, CO), and smoke production. This comprehensive instrumentation enables early identification of smouldering onset, thermal runaway, and self-sustained propagation. Smouldering velocities can be derived from temperature isochrones along the specimen height, providing quantitative data on smouldering spread that are otherwise inaccessible.

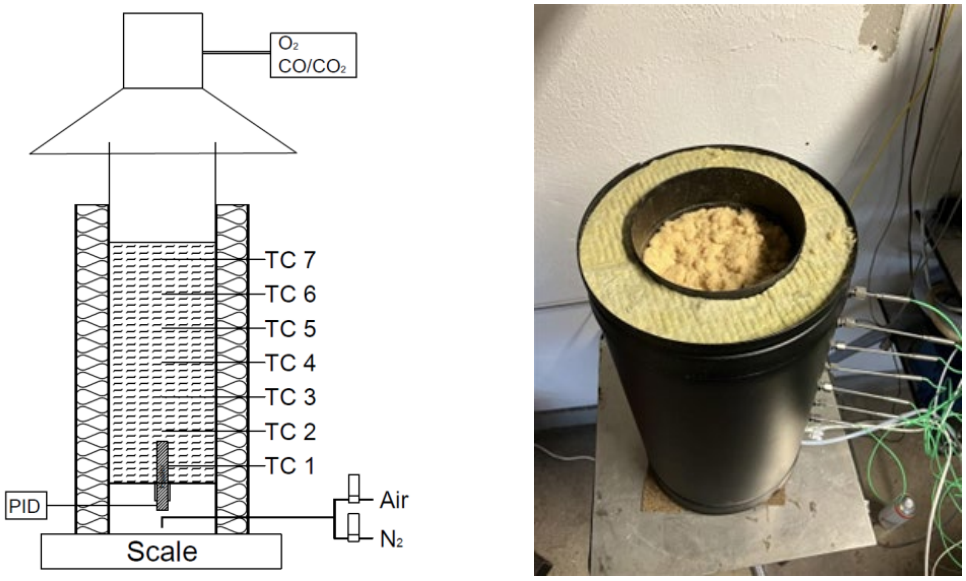


Figure 54: Prototype of the Controlled-Atmosphere-Smouldering-Propagation-Reactor (CASPR) developed at DBI

While CASPR is not currently intended as a classification or regulatory test, it provides high-resolution experimental data suitable for mechanistic understanding, comparative material assessment, and validation of smouldering and pyrolysis models. As such, CASPR complements standardised fire tests by addressing smouldering-specific hazards, which are particularly relevant to bio-based insulation materials in concealed or post-flashover decay scenarios.

5.6.2. Advanced smouldering models

The current state of the art in smouldering modelling is moving from simplified heat-transfer or empirical descriptions toward physics-based porous-media models that explicitly couple heat transfer, gas flow, species transport, moisture effects, and heterogeneous solid-phase reactions. For many materials, including bio-based insulation, models such as [36] are now capable of reproducing key observables such as temperature profiles and smouldering spread rates under controlled conditions. From a practical perspective, this represents a significant advancement compared to earlier empirical or purely thermal models. The tools can support qualitative risk assessment and enable systematic parametric studies (e.g. influence of density, airflow, or moisture content), which are difficult to achieve experimentally alone.

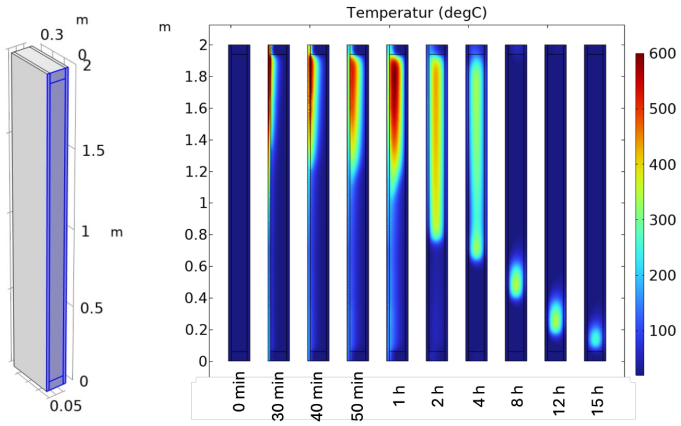


Figure 55: Simulation of smouldering in a timber frame component over 15 h, validated with experimental data [82]

Looking ahead, these models have strong potential to complement and partially replace extensive fire testing. Smouldering processes typically evolve over long time scales, making experimental campaigns time-consuming and resource intensive. In this context, modelling can be used to pre-screen material configurations, identify critical parameter ranges, and reduce the number of physical tests required. This is particularly relevant for bio-based insulation systems, where variations in density, moisture content, and installation conditions would otherwise require a large number of experiments to adequately assess.

In addition, modelling offers advantages in exploring scenarios that are difficult to reproduce experimentally, such as concealed smouldering in complex assemblies, varying ventilation conditions, or long-term propagation. Once sufficiently validated, models could support the interpretation of test results, help extrapolate beyond tested configurations, and assist in the development and optimisation of fire test methods themselves.

6. SUMMARY AND OUTLOOK

This report demonstrates that bio-based insulation materials can play a significant role in low-carbon construction, but their fire behaviour, particularly with respect to smouldering, requires careful consideration at the system level rather than solely at the material level. While these materials offer clear environmental advantages, their inherent combustibility and susceptibility to smouldering introduce distinct fire safety challenges that are not fully addressed by current regulatory frameworks and standardised test methods.

A central finding is that smouldering constitutes a primary fire risk for bio-based insulation. Unlike flaming combustion, smouldering is slow, difficult to detect, and can persist for extended periods, including after the primary fire event has been extinguished. This creates specific hazards such as concealed fire spread, delayed structural failure during the cooling phase, and the release of toxic gases, particularly carbon monoxide. Several case studies and experiments confirm that smouldering can lead to prolonged firefighting operations, repeated re-ignition, and significant operational challenges.

At the same time, the report shows that fire performance is primarily controlled by the construction system rather than the insulation material itself. Robust and continuous protective coverings, appropriate detailing, and well-designed assemblies can effectively prevent or significantly delay smouldering initiation during the critical early stages of fire exposure. Conversely, local weaknesses, such as penetrations, joints, or poorly executed details, can govern fire behaviour and negate otherwise effective protective measures. This highlights the importance of system integrity and execution quality in construction projects.

The studies reviewed address smouldering in several test contexts, including reaction-to-fire tests, fire-resistance tests on building components, and façade fire tests. These tests address different aspects of fire performance, showing that smouldering should be considered across multiple functional requirements rather than as an isolated material property.

A key gap identified throughout the report is the limited information that current fire classifications provide about concealed smouldering and its longer-term consequences. Assessing a product's propensity to smoulder is only one part of addressing this gap. The smouldering resistance of the complete construction must also be considered, including its ability to limit smouldering propagation and maintain required safety functions during and after fire exposure. The challenge is therefore to ensure that assessment methods provide sufficient evidence to demonstrate that the intended construction meets the fire-safety requirements established by national or regional authorities.

A dedicated, standardised assessment method for construction-level smouldering resistance, as defined in this report, has not yet been established. Developing such a method requires representative exposure conditions, an observation period that captures delayed behaviour, and performance criteria addressing smouldering propagation and the maintenance of required safety functions. This is an important research need for supporting the assessment of constructions incorporating bio-based insulation.

Future research should address smouldering at the construction-system level, considering interactions between insulation, timber framing, wood-based sheathing and protective layers. This should include assemblies with non-combustible insulation and investigate whether adjacent combustible components provide pathways for smouldering to spread beyond barriers installed within the insulation layer. Future work should also establish proportionate and economically feasible documentation routes for bio-based insulation systems, balancing fire-safety requirements with practical implementation.

Developing these routes lies beyond the scope of this white paper, but it is important to avoid unnecessary testing burdens and barriers to market entry. The report does not propose blanket additional testing requirements for currently accepted solutions, nor does it imply that every variation in construction build-up or material combination requires a separate smouldering test.

Another research priority is the long-term durability of fire performance in bio-based insulation, including the effectiveness of fire-retardant and smouldering-retardant treatments after ageing and exposure to moisture or other relevant service conditions. This should establish whether initial test results remain representative throughout the intended service life. The influence of moisture should generally be considered when conducting smouldering ignition and propagation testing.

From a design perspective, a risk-informed approach is essential for the use of combustible bio-based insulation. Instead of excluding materials solely based on classification, the report supports performance-based strategies that assess both the likelihood of smouldering initiation and its potential consequences. Effective mitigation measures include preventing ignition through protective layers, limiting fire spread through compartmentation and barriers, and enabling detection and intervention through appropriate firefighting strategies. In this context, system-level testing, advanced smouldering tests, and modelling approaches are emerging as important tools to support engineering judgement and reduce uncertainty.

Looking ahead, further development is needed to bridge the gap between research and practice. This includes improved and standardised methods for assessing smouldering (such as BioFireAssess), better representation of real construction conditions, and the integration of risk-informed and system-based approaches into fire safety design. In addition to design measures, future strategies should increasingly address the management of smouldering risks during construction, renovation, and post-fire intervention. Such routes could combine product screening with representative testing of product and construction families, supported by defined fields of application and variation limits, with project-specific testing reserved for cases not adequately covered by existing evidence.

In summary, bio-based insulation materials can be used safely in buildings, including more complex applications, provided that their specific fire behaviour, especially smouldering, is explicitly addressed. The transition from prescriptive, material-based assessment to system-oriented, performance-based design is therefore a key enabler of their broader, more reliable use in sustainable construction.

DBI

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APPENDIX A – LIST OF RESEARCH PROJECTS

Germany:

NiBreHoDae – Entwicklung eines porösen nichtbrennbaren Dämmstoffs mit anorganisch gebundener Holzfasermatrix (2025–2028) Info

NiBreHoDae aims to develop a porous insulation material combining wood fibres with inorganic binders and additives, targeting reaction-to-fire class A2 according to EN 13501-1. Fire behaviour and emissions are investigated alongside technical performance, recyclability and environmental impacts. The project also examines potential applications in façade elements and external thermal insulation composite systems. The targeted classification is a research objective rather than a confirmed outcome.

HoBraTec – Optimierung der Brandbekämpfungsmethoden und -techniken für Gebäude in moderner Holzbauweise (2021–2024) Final Report: Part 1, Part 2, Part 3

Focused on modern timber construction, HoBraTec investigated effective firefighting strategies and intervention techniques for cavity fires and smouldering insulation. It included training modules for fire brigades, technical guidelines, and assessments of infrared detection, CO monitoring, and removal techniques for fire-damaged bio-based insulation.

PyroProBiD – Entwicklung eines Pyrolyse-Prognosemodelles für Dämmstoffe aus nachwachsenden Rohstoffen (2020–2023) Final Report

This project developed a predictive model to simulate pyrolysis and smouldering behaviour in bio-based insulation materials under various boundary conditions. The model supports risk assessments and helps engineers evaluate design alternatives and covering configurations to minimize smouldering risks.

InnoDämm – Glimmgeschützte Holzfaserdämmung (2019–2021) Final Report

InnoDämm investigated treatments intended to suppress sustained smouldering in wood-fibre insulation boards. Fraunhofer WKI worked with ET Brandschutz and Gutex to develop and incorporate protective formulations into insulation products. The research included testing in a dedicated smouldering apparatus and according to EN 16733, together with assessments of thermal conductivity, density and water absorption. Industrial-scale manufacturing trials addressed the feasibility of implementing the formulations in production.

TIMPuls – Fire safety and protection measures for multi-storey timber buildings (2017–2021) Final Report

TIMPuls provided the scientific basis for updating building codes related to timber construction. It focused on fire resistance of timber elements, smouldering risk, and design adaptations to allow broader use of renewable insulation within multi-storey buildings. Results were instrumental in shaping the MHolzBauRL 2020 and supporting broader policy decisions.

Mehr als nur Dämmung (More than just insulation) (2016–2020) Final report

"Mehr als nur Dämmung" is a research project that examined the various benefits of insulating materials made from renewable raw materials. It is not only investigating fire behaviour but also thermal insulation, their ecological impact, moisture protection, emission, and soundproofing. The project was funded by the Federal Ministry of Food and Agriculture (BMEL) via the Agency for Renewable Resources (FNR). The aim was to increase the market potential of insulation materials made from renewable raw materials and to improve their application for manufacturers, planners and processors. The final report is available in German.

Standardisierung der Leistungsfähigkeit biogener Dämmstoffe (2015–2018)
Final report This project aimed to develop a reliable, standardized calculation approach for such applications. It included experiments to determine missing thermal properties of cellulose and wood fibre insulation, followed by simulations and fire tests on typical wall and floor setups. These tested how insulation layers influence heat transfer, charring, and the load-bearing capacity of timber frames. The result is a validated engineering method for verifying fire resistance (up to 90 minutes) of timber elements with bio-based insulation, intended for inclusion in the revision of EN 1995-1-2.

Direktverputzte Strohballenbauteile für Gebäudeklasse 4 – Teilprojekt Brandschutztechnische Untersuchungen (2014) Final Report
This project focused on the fire performance of directly rendered straw-bale construction in mid-rise buildings. It evaluated render systems, fire resistance classes, and practical integration of straw bale walls into the GK 4 category, addressing both technical and regulatory barriers.

Investigations into the optimization and standardization of insulation materials made from renewable raw materials (2004–2007)
As one of the earliest projects, this study established foundational knowledge on the flammability, thermal degradation, and treatment methods for bio-based insulations. It evaluated the effectiveness of flame retardants and multi-layer covering systems under thermal stress.

Denmark:

BioFireAssess: Assessing the Fire Risks of Bio-based Insulation Materials through Innovative Testing and Modeling Approaches (2025–2027) Info
BioFireAssess addresses the lack of standardized criteria for evaluating the smouldering behaviour of bio-based insulation materials. Current knowledge gaps prevent designers from confidently using these materials to reduce embodied carbon in buildings. The project aims to close fundamental knowledge gaps on smouldering initiation, spread, and consequences of smouldering. Furthermore, the aim is to develop and validate a hybrid assessment method combining reduced-order testing and numerical modeling. Finally, it aims to establish a practical framework for quantifying smouldering risk, supporting real-world application in design and consultancy.

MUDP – The Biogenic Modular Building – Construction, Fire, and Architecture (2024-2026)
This project evaluates the fire safety of biogenic construction materials—such as straw, reed, grass, hemp, and eelgrass—focusing on their fire behaviour, classification, and legal requirements in Denmark. It compares prescriptive and performance-based fire safety design approaches and compiles test results from various bio-based materials. The study recommends tailored fire safety strategies, including advanced testing and performance-based design, to enable the safe and sustainable use of biogenic materials in low-rise buildings.

BioFacades:UpHigh (2022-2025) Final Report
The project BioFacades:UpHigh aimed to push the boundaries of how high we can construct facades in Denmark using wood and other bio-based materials that are neither fire-protected (e.g., with fire retardants, fire paint, or clay) nor equipped with sprinklers. Based on 10 full-scale facade fire tests and drawing on three specific example buildings, the project partners demonstrated that structural design solutions in the facade can prevent the spread of fire and provide a safe alternative to existing pre-accepted solutions.

Sweden:

Biobaserade byggnadsmaterial – en kunskapsöversikt om brandtekniska egenskaper (2023) Final Report
This research project, funded by Brandforsk, examined the fire safety of emerging bio-based building materials such as hemp, straw, grass, clay, and fungi-based products. Its main objective was to collect and assess existing knowledge on their fire behaviour, classification methods, and application-related challenges.
The study identified gaps in fire testing standards, particularly concerning penetrations and recessed installations, and revealed inconsistencies in fire performance across different products and manufacturers. It also found a lack of data on how these materials respond to firefighting methods, such as water application. By addressing these issues, the project aimed to lay the foundation for safer integration of bio-based materials into construction, supporting their broader use in sustainable building while meeting essential fire safety requirements.

Norway:

A study of the fire performance of combustible thermal insulation through fire experiments (2025) Final Report
The study investigated the fire behaviour of combustible thermal insulation in timber-frame constructions, focusing on PIR, wood fibre and cellulose. Its purpose was to examine how these materials influence temperature development and fire damage when installed behind protective cladding, including situations with damaged cladding or penetrations for technical installations. It also assessed the protective performance of different claddings and the behaviour of the junction between walls and roofs. The tested products comprised PIR boards, wood-fibre batts and loose-fill insulation, and cellulose batts and loose-fill insulation. Glass wool and stone wool were included as non-combustible reference materials.

France:

MODEFIRE – Characterization and Modeling of Smoldering Fire Behavior in Bio-Based Insulation Materials (2025-present) Info
MODEFIRE investigates smouldering in bio-based insulation materials, particularly agro-concretes. The project combines thermophysical characterisation, experimental investigations of smouldering propagation, and development of a multiphysics model. It also examines fire barriers intended to limit smouldering. The research aims to support technical recommendations for the use of bio-based insulation in buildings.

INCSEB – Innovative Ultra-Low Carbon Building Steel Envelope Systems with Bio-Based Insulation (2021–2025) Publications and workshop presentations
INCSEB developed five steel building-envelope systems incorporating wood-fibre insulation, covering wall cladding and roof applications. Its testing programme addressed reaction to fire, fire resistance, fire propagation and smouldering, alongside mechanical, thermal, acoustic and environmental performance. The project provides a system-level perspective on bio-based insulation in metal-clad assemblies, extending the discussion beyond timber construction.