BUILDING RESILIENT FUTURES: CLIMATE SUSTAINABILITY AND COMMUNITY EMPOWERMENT IN WB AND EU
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FIRE SAFETY OF ENERGY-EFFICIENT BUILDINGS: THE ROLE OF COMBUSTIBLE AND CIRCULAR MATERIALS

Abstract

The global shift towards sustainable construction and energy-efficient building design has brought forward new challenges in fire safety. Modern energy-efficient buildings frequently incorporate advanced insulation systems, airtight envelopes and renewable or recycled construction materials, many of which are combustible. This paper examines the fire safety implications of integrating such materials, particularly those used to enhance thermal performance or those selected to support circular economy principles, such as reused wood, biocomposites and plastic-based insulation. While these materials offer environmental benefits, they may significantly increase the fire load, release toxic smoke and accelerate flame spread, especially in highly insulated and airtight buildings.

The paper reviews current trends in material use, evaluates relevant fire performance standards (e.g., Euroclass system) and analyzes fire behavior of key materials such as expanded polystyrene (EPS), polyurethane (PU), wood fiber boards and recycled plastics. A specific emphasis is placed on the balance between sustainability and safety, highlighting the need for integrated design approaches that consider fire risk from the earliest stages of planning.

The study also reviews best practices in fire prevention strategies, such as compartmentation, fire-resistant cladding systems and the use of intumescent coatings. The paper calls for updated regulatory frameworks and testing protocols that address the evolving risks in energy-efficient and circular construction, ensuring that green building efforts do not compromise occupant safety. Case studies of recent fire incidents are discussed to illustrate the complex interactions between energy efficiency measures, material combustibility and fire performance. Ultimately, the research underscores the importance of harmonizing energy efficiency, material circularity and fire safety in future building design.

Keywords

Fire safety, energy-efficient buildings, combustible materials, circular economy, insulation, wood, recycled materials, sustainable construction, fire-resistant design

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1. INTRODUCTION

The contemporary built environment is undergoing a rapid transformation driven by the urgent need to reduce greenhouse gas emissions and minimize the environmental footprint of construction. Energy-efficient building design, supported by global initiatives such as the European Green Deal and the Paris Climate Agreement, [1-2], has placed sustainability at the forefront of architectural and engineering practice. The adoption of advanced thermal insulation, airtight building envelopes and the integration of renewable or recycled construction materials has become increasingly common. These measures undoubtedly contribute to energy savings and align with principles of the circular economy.

However, the use of new materials and design strategies has introduced unforeseen challenges in terms of fire safety. Many energy-efficient materials, particularly plastic foams, wood-based composites and recycled plastics, exhibit high combustibility and can release large quantities of toxic gases under fire exposure.

Due to limited ventilation pathways, in case of airtight buildings fire development is not faster but more severe than in buildings without thermal insulation and energy efficient windows. In the “unsealed” buildings, the availability of oxygen enables sustained combustion and repetition of temperature peaks, with maximum temperatures near the fire source. This led to higher thermal radiation and longer exposure to elevated temperatures. Such conditions create an immediate and severe thermal threat to occupants, while the higher smoke layer position allowes for somewhat better visibility and escape possibilities. By contrast, in the “sealed”, or airtight buildings, the limited oxygen supply reduces the overall intensity and duration of open flames but creates a hazardous environment dominated by toxic smoke, low oxygen levels and severely reduced visibility. Moreover, the accumulation of unburned gases significantly increases the risk of backdraft if ventilation is suddenly introduced. Thus, while unsealed buildings present greater danger from intense heat and prolonged fire duration, airtight buildings pose a more insidious risk through toxic atmosphere, oxygen depletion and explosive fire behavior.

This duality of sustainability and safety presents a central dilemma: while environmentally friendly, certain construction choices may inadvertently increase the vulnerability of buildings to fire.

This paper critically examines the implications of material choices in sustainable construction for fire safety. It provides an overview of key combustible materials used in energy-efficient and circular buildings, evaluates their fire behavior and reviews relevant regulatory frameworks such as the Euroclass classification system. It also highlights fire safety design strategies, including compartmentation, protective coatings and advanced façade systems, while underscoring the need for updated standards and integrated design approaches.

2. MATERIALS IN ENERGY-EFFICIENT AND CIRCULAR CONSTRUCTION

Fire safety considerations in energy-efficient and circular construction are essential to achieving both sustainability and resilience. The thermal, environmental and fire characteristics of insulation materials, wood-based and bio-composites and recycled polymers collectively influence

energy performance, carbon footprint and overall safety. Figure 1 summarizes these material classes by energy efficiency, circularity and fire performance.

2.1. PLASTIC-BASED INSULATION

Expanded polystyrene (EPS) and polyurethane (PU) foams are among the most widely used materials for improving thermal performance. Their low thermal conductivity enables significant reductions in heating and cooling energy demand. However, materials such as expanded polystyrene (EPS) and polyurethane (PU) foams, while highly effective in improving energy efficiency, are problematic from both a circularity and fire safety perspective.

Expanded Polystyrene (EPS) comes from fossil-based feedstocks and is hard to recycle. Mechanical and chemical recycling methods exist, but large-scale recovery is rare due to contamination during demolition, transport challenges and the low value of recycled EPS. Polyurethane (PU) foams face even bigger end-of-life issues. As thermoset plastics, they cannot be remelted or turned into high-value products. Some downcycling and experimental chemical recycling processes exist, but industrial use is still very limited.

EPS and PU are highly combustible, characterized by low ignition temperatures and rapid flame spread once ignited and the release of dense, toxic smoke containing carbon monoxide and hydrogen cyanide and melts and drips under heat exposure. Past fire incidents in insulated façades have demonstrated that these materials can facilitate vertical fire spread if not adequately protected.

2.2. WOOD AND BIOCOMPOSITES

Wood fiber insulation boards, laminated timber elements and bio-composites, often formulated with agricultural residues or natural fibers bound with biobased or synthetic resins, are increasingly preferred for their renewable origins, carbon sequestration potential and comparatively low embodied energy.

Beyond their environmental benefits, these materials can be engineered to achieve meaningful levels of fire resistance through treatments, charring behavior optimization and protective encapsulation. Nevertheless, their organic content inherently contributes to the overall fire load, which requires careful consideration in performance-based fire design.

From an energy efficiency perspective, wood fiber boards provide moderate thermal performance and some heat storage capacity, so they can contribute to seasonal comfort and to reduced heating and cooling demands. However, their performance depends strongly on board density, moisture content and climate.

2.3. RECYCLED PLASTICS AND CIRCULAR MATERIALS

The transition toward a circular economy has accelerated the reuse of plastics, rubber and other polymers in building products such as insulation boards, façade cladding and interior finishes. These materials offer clear environmental advantages by diverting waste from landfills and reducing demand for virgin feedstocks.

However, the heterogeneity of recycled polymer streams introduces significant challenges in fire safety assessment. Variations in polymer type, filler content and the presence of additives or contaminants can lead to unpredictable ignition characteristics, inconsistent flame spread rates and variable smoke toxicity. Such variability complicates classification under standardized fire testing protocols and hinders reliable performance prediction.

Figure 1. Comparison of Considered Materials by Energy Efficiency, Circularity and Fire Safety, [3-5]

	Energy Efficiency (Thermal Performance)	**Circularity (End-of-Life & Recycling)**	**Fire Safety (Combustibility & Smoke)**
Expanded Polystyrene (EPS)	★★★★☆ very good, low λ-value ~0.030–0.040 W/mK	★☆☆☆☆ low recyclability; mostly landfilled/incinerated	★☆☆☆☆ ignites easily, melts and drips, rapid flame spread, produces dense smoke
Polyurethane (PU) Foams	★★★★★ excellent, very low λ-value ~0.020–0.030 W/mK	★☆☆☆☆ thermoset → poor recyclability; limited downcycling	★☆☆☆☆ high heat release, toxic smoke with HCN and CO, difficult to protect without additional systems
Wood Fiber Boards	★★★☆☆ moderate, λ-value ~0.038–0.050 W/mK	★★★★☆ renewable, reusable, recyclable, biodegradable	★★☆☆☆ combustible but steady burning; performance improves with additives and protective layers
Cellulose Insulation	★★★☆☆ moderate, λ-value ~0.038–0.045 W/mK	★★★★★ recycled origin, biodegradable, circular	★★☆☆☆ combustible; treated with fire retardants to slow ignition and flame spread
Mineral Wool (reference)	★★★★☆ good, λ-value ~0.030–0.040 W/mK	★★★★☆ recyclable, durable, inert	★★★★★ non-combustible, Euroclass A1, excellent fire resistance

3. REGULATORY FRAMEWORKS AND STANDARDS

3.1. EUROCLASS SYSTEM

The Euroclass system (EN 13501-1), [6], is the prevailing European standard for reaction-to-fire classification. It assesses ignitability, flame spread, heat release, smoke production and flaming droplets, providing a harmonized approach across EU member states. Materials are classified from A1 (non-combustible) to F (no performance determined). Table 1 presents the Euroclass ratings of selected materials, together with their key fire behavior characteristics and relevant design considerations.

Table 1. Euroclass Classification of Selected Materials, [7-10]

Material	Euroclass Rating	Key Fire Behavior Characteristics	Notes
Expanded Polystyrene (EPS)	E–F	Easily ignitable, melts and drips, rapid flame spread	Needs protective cladding
Polyurethane (PU)	C–E	High heat release, toxic smoke (HCN, CO)	Fire retardants improve performance but limited effectiveness
Wood Fiber Board	C–D	Burns steadily, contributes to fire load, produces smoke	Performance varies with density and fire-retardant additives
Recycled Plastic Insulation	Variable (D–F)	Unpredictable fire behavior, inconsistent composition	Lack of standardized testing protocols

3.2. LIMITATIONS OF CURRENT TESTING

While the Euroclass system provides a structured approach, critics argue that small-scale tests do not always capture real-world fire dynamics, particularly for complex assemblies such as insulated façades. Standardized tests often focus on isolated materials rather than entire building systems. For example, EPS insulation may achieve a Euroclass E rating, but when combined with protective cladding, adhesives and air cavities, fire performance can vary significantly. Real fire scenarios also involve multiple materials interacting, which cannot be fully represented in laboratory conditions. This discrepancy highlights the need for updated testing protocols that better reflect contemporary energy-efficient building designs.

4. CASE STUDIES OF FIRE INCIDENTS

4.1. DIJON FIRE, (DIJON, 2010)

The fire started from an external rubbish container resulting in vertical spread on the façade system. The façade is an ETICS system with polystyrene insulation, [11-12], Figure 2.

4.2. LACROSSE APARTMENT FIRE, (MELBOURNE, 2014)

The 2014 Lacrosse Apartment fire in Melbourne exposed the extreme risk of combustible façades. Polyethylene-core aluminum composite panels enabled flames to race from an eighth-floor balcony to the roof within minutes. Subsequent investigations revealed failures in product certification, regulatory oversight and compliance enforcement, [13-14], Figure 2.

4.3. GRENFELL TOWER, (LONDON, 2017)

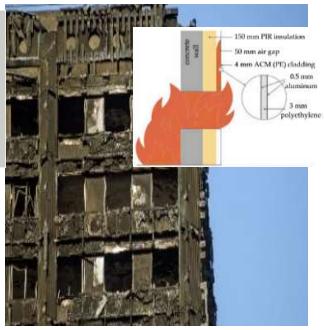
The Grenfell Tower tragedy underscored the dangers of combustible insulation and cladding systems. Polyisocyanurate (PIR) and aluminium composite panels contributed to rapid vertical fire spread, leading to huge consequences. While the building complied with certain regulatory requirements, the fire revealed deficiencies in both product testing and risk evaluation frameworks, [15-16], Figure 2.



Dijon, France 2010 Façade Fire, [11-12]



Lacrosse Apartment Fire (Melbourne, 2014), [13-14]



Grenfell Tower Fire (London, 2017), [15-16]

Figure 2. Case Studies of Fire Incidents

4.4. OTHER NOTABLE INCIDENTS

Several façade fires across Europe, the Middle East and Asia have involved EPS and PU insulation boards or other plastic-based insulation, often in combination with combustible cladding. These cases demonstrate that even materials deemed “acceptable” in isolated testing can fail under real-world conditions, particularly when used in airtight, highly insulated structures.

5. FIRE SAFETY DESIGN STRATEGIES

Effective fire safety in modern circular buildings requires a multi-layered approach that combines prevention, containment and system-level resilience. The following strategies highlight key measures:

- **Compartmentation:** One of the most effective methods of containing fire is compartmentation, which involves subdividing a building into fire-resistant sections, Figure 3. This strategy prevents flame and smoke spread, buying critical time for evacuation and firefighting.

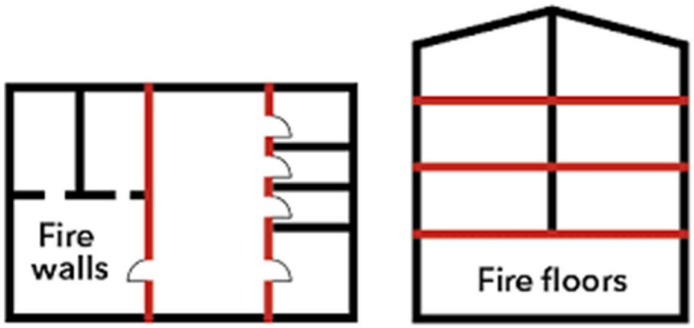


Figure 3. Compartmentation of Building, [17]

- **Protective Cladding and Intumescent Coatings:** The application of non-combustible cladding or intumescent coatings can significantly improve the fire resistance of combustible materials, Figure 4. Intumescent paints, for instance, swell when exposed to heat, forming a protective char layer that insulates the underlying substrate.



Figure 4. Intumescent Coatings, [18]

- **Ventilation and Smoke Control:** Given the airtight nature of modern energy-efficient buildings, controlled ventilation and smoke extraction systems are essential. Mechanical smoke control systems can prevent toxic gas accumulation, which is often the primary cause of fatalities in residential fires.
- **Fire-Safe Material Innovation:** Ongoing research into bio-based composites with embedded fire retardants, or hybrid insulation materials that combine organic and inorganic components, shows promise. Such innovations aim to merge sustainability with acceptable fire performance.
- **Balancing Sustainability and Safety:** The integration of circular and energy-efficient principles in construction cannot be pursued in isolation from safety

concerns. A holistic approach is required, Figure 5, where energy performance, carbon reduction and fire safety are addressed simultaneously from the early design stages. This entails collaboration between architects, engineers, material scientists and fire safety professionals. Furthermore, regulatory frameworks must evolve to account for new risks associated with combustible sustainable materials. Performance-based design, rather than prescriptive rules, offers a pathway forward by evaluating how entire building systems behave under realistic fire scenarios.

Table 2 summarizes key fire mitigation strategies for energy-efficient, circular buildings, outlining their primary function and providing example applications. Together, these measures show how thoughtful design choices, material selection, and performance-based approaches can enhance fire safety while supporting sustainability objectives.

Table 2. Fire Mitigation Strategies in Energy-Efficient Buildings

Strategy	**Function**	**Example Application**
Compartmentation	Limits fire spread between zones	Fire-rated walls and floors
Fire-resistant cladding	Protects combustible insulation in façades	Non-combustible mineral-based panels
Intumescent coatings	Expands under heat to insulate combustible core	Timber beams, steel structures
Mechanical smoke control	Prevents toxic gas buildup	Pressurized stairwells, exhaust fans
Material innovation	Combines sustainability with fire safety	Bio-based composites with embedded retardants

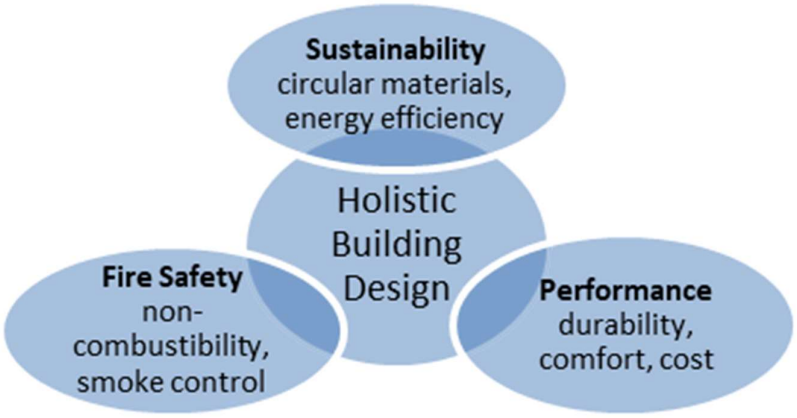


Figure 5. Integrated Design Approach for Safe and Sustainable Buildings

6. CONCLUSION

The global push for sustainable and circular construction has introduced a new generation of building materials that, while environmentally beneficial, often present elevated fire risks. Plastic-based insulation, wood composites and recycled polymers enhance energy performance but can accelerate fire growth, produce toxic smoke and challenge existing safety frameworks. Current testing methods, though useful, fail to fully capture the complexities of modern assemblies and building envelopes.

Best practices such as compartmentation, protective coatings and smoke control systems can mitigate some of these risks, but they must be paired with more rigorous standards and updated regulations. Lessons from recent fire incidents, most notably Grenfell Tower, emphasize the critical importance of harmonizing sustainability with safety.

Ultimately, future building design must embrace integrated strategies where energy efficiency, material circularity and fire resilience are not competing objectives but interdependent aspects of sustainable construction. Only through such holistic approaches can the built environment achieve its dual goals of environmental responsibility and occupant protection.

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