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Fire Safety Challenges of ‘Green’ Buildings and Attributes

Final Report by:

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Foreword

In 2012, the Fire Protection Research Foundation published the report, Fire Safety Challenges of Green Buildings, the objectives of which were to a) systematically document a set of green building design elements that may increase fire safety hazards, and, b) share best practices identified via the search with respect to fire hazard risk mitigation associated with green building design elements.

This effort identified more some 80 'green' building features and technologies, identified a set of 22 potential sources of increased hazard or risk associated with the 'green' features and technologies, identified several fire and other safety events associated with the 'green' features and technologies, and presented a relative risk matrix as a qualitative representation of the 'additional' hazard or risk presented by 'green' buildings and features.

In the six and a half years since the project report was published, there have been several major fire events, which involved 'green' building features or technologies, notably the Grenfell Tower fire in London (combustible insulation), the Dietz & Watson cold storage warehouse in Delanco, New Jersey (photovoltaic panels, combustible insulation), and a spate of fires in buildings under construction using lightweight timber framing. While each of these can be categorized in many ways, they (and many others) include materials, systems, technologies and features that are considered 'green' or sustainable. There has also been new research and some regulatory change.

Therefore, the Foundation initiated this project with the goal to conduct a global information search into fire events involving green / sustainable building materials, features and technologies, and into research, regulatory changes, engineering approaches, risk mitigation strategies, and firefighting tactics associated with fire challenges with green / sustainable building materials, features and technologies, which have emerged since the publication of the 2012 report, Fire Safety Challenges of Green Buildings.

The Fire Protection Research Foundation expresses gratitude to the report authors Brian Meacham, who is with Meacham Associates located in Shrewsbury, MA, USA, and Margaret McNamee, who is with Lund University located in Lund, Sweden. The Research Foundation appreciates the guidance provided by the Project Technical Panelists, the funding provided by the project sponsors, and all others that contributed to this research effort.

About the Fire Protection Research Foundation

The Fire Protection Research Foundation plans, manages, and communicates research on a broad range of fire safety issues in collaboration with scientists and laboratories around the world. The Foundation is an affiliate of NFPA.

About the National Fire Protection Association (NFPA)

Founded in 1896, NFPA is a global, nonprofit organization devoted to eliminating death, injury, property and economic loss due to fire, electrical and related hazards. The association delivers information and knowledge through more than 300 consensus codes and standards, research, training, education, outreach and advocacy; and by partnering with others who share an interest in furthering the NFPA mission.

All NFPA codes and standards can be viewed online for free.

NFPA's membership totals more than 65,000 individuals around the world.

Keywords: green buildings, sustainable, fire safety, risk, performance, resilience

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Fire Safety Challenges of 'Green' Buildings and Attributes

Final Report

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Executive Summary

In 2012, the Fire Protection Research Foundation (FPRF) supported a literature review related to fire safety challenges of 'green' (sustainable) building materials, systems (technologies) and features. The aims of that work were to: identify documented fire incidents in 'green' buildings; define a specific set of elements in 'green' building design, including configuration and materials, which, without mitigating strategies, increase fire risk, decrease safety or decrease building performance in comparison with 'traditional' construction; identify and summarize existing best practice case studies in which the risk introduced by specific 'green' building design elements has been explicitly addressed; and compile research studies related to incorporating building safety, life safety and fire safety as an explicit element in 'green' building indices, identifying gaps and specific needed research areas.

In the eight years since the 2012 report was published, there have been several major fire events, which involved 'green' materials, systems and features (collectively, 'green' attributes) in buildings, including the tragic Grenfell Tower fire in London (involving combustible insulation); the Dietz & Watson cold storage warehouse in Delanco, New Jersey (involving photovoltaic panels, combustible insulation); and the 2019 energy storage system (ESS) explosion and fire in Arizona. While each of these can be categorized in many ways, they (and many others) include materials, systems and features that are considered 'green' or sustainable. Additionally, since 2012, there has been significant research into the fire performance of a wide range of 'green' attributes of buildings, and numerous changes and/or additions to regulations, standards and guidance around managing and mitigating associated fire hazards and risks. Further, new 'green' attributes continue to be developed and implemented, which could present fire hazards or risks if unmitigated.

In response to the major advances that have taken place since 2012, this work presents a comprehensive review of how the landscape of fire safety challenges of 'green' attributes of buildings has developed since 2012. It is based on a global information search into: fire events involving 'green' and/or sustainable building materials, systems and features; emerging 'green' building materials, systems and features; and research, regulatory changes, engineering approaches, risk mitigation strategies, and firefighting tactics associated with fire challenges with 'green' and/or sustainable building materials, systems and features. While the research is comprehensive is scope, it is not exhaustive in detail, given the extent of advancement in these areas which has occurred since 2012. And, while significant advancements have been made, gaps remain, and strategies for proactively incorporating fire performance into development of new 'green' building materials, systems and features (product development) are lacking, the tools to proactively assess the fire performance of 'green' building materials, systems and features at the product level (e.g., fire performance testing), and as installed in buildings, are lacking, and a broader building regulatory framework and design philosophy for achieving sustainable and fire resilient (SAFR) buildings is also lacking.

A fundamental aim of this review is to understand the extent to which unintended fire hazards and risks associated with 'green' attributes of building have been addressed, are being considered, and continue to emerge. The risk framework presented in Chapter 6 is at the core of this analysis, surrounded by three main themes: societal objectives (to create modern, 'green' buildings which do not endanger our climate); the attributes of the buildings and communities which express these societal objectives (materials, systems and design features); and, finally, control mechanisms that are put in place to ensure that these buildings and communities are fire safe (regulations, standards and guidelines). This framework can be pictured as a tetrahedron (triangular pyramid) with four faces, i.e., "Risk and Performance" at the base, and "Societal Objectives", "Attributes", and "Control Mechanisms" as the faces, see Figure ES.1a. For simplicity, the 2D projection of the 3D concept (see Figure ES.1b) has been used to exemplify the system and the interactions between the faces of the tetrahedron.

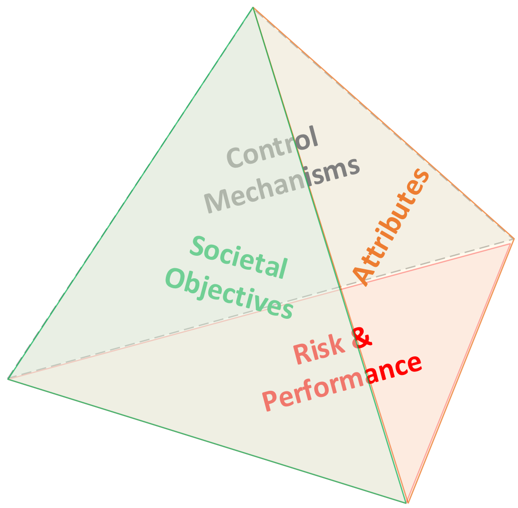

Figure ES.1a 3D Depiction of Risk Tetrahedron for 'green' Buildings

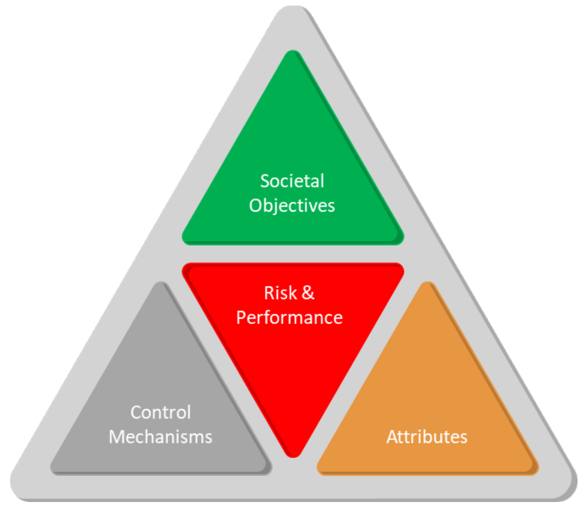

Figure ES.1b 2D Projection of Risk Tetrahedron for 'green' Buildings with "Risk & Performance" at the Center of the Figure.

"Risk & Performance" forms the theoretical base of the tetrahedron as this is the hinge-pin on which much of the assessment is based. The literature study indicates that while fire hazards and risks, which have previously been identified, have been addressed in many regards, fire safety is still considered relatively late in the design process and does not always carry through to the operational phase of a building. Inclusion of fire safety in the early stages of product and system development, and in building or community planning and design, would help to alleviate many fire safety issues before they truly emerge, e.g. questions of material fire performance, system design, and first responder accessibility. The present study indicates that there are a number of areas which merit additional research to develop our understanding of the risks they represent, e.g. PV-systems, various façade systems, mass and high-rise wood construction, densification, energy storage systems, renovation practices and the use of recycled materials. It also highlights the need for additional work in developing risk and decision tools for assessing and informing design and mitigation strategies.

With respect to "Societal Objectives", this has special significance in the context of 'green' buildings as historically the fundamental objective in the context of 'green' buildings has focused on sustainability. Sustainability has traditionally been synonymous with environmental safety; but, in recent years has come to encompass the three established dimensions of environmental, economic and social sustainability. However, this view of sustainability arguably does not embrace fire safety, in particular fire resiliency. It is argued that there is a need to broaden our basic understanding of societal objectives as being many and not one, which must work together, and to include resilience into the context of 'Sustainable and Fire Resilient' (SAFR) buildings and communities. The underlying principle is that inclusion of risk and performance considerations into the overall assessment of whether particular structures meet design criteria across all societal dimensions allows for more robust or 'safer' solutions for individual buildings, responding fire service personnel, and the community at large.

'Green' building materials, systems and features are collectively referred to as the "Attributes" of a building. These attributes are designed to meet societal objectives and, just as for societal objectives, these need to be considered in terms of risk and performance. Research indicates that new materials and systems are constantly being developed. Fire incidents that have been reported indicate that sometimes the adoption of such systems can have unexpected consequences when safety considerations are not considered early in the development phase or where unexpected combinations of materials are used to create and install systems outside of the original specifications. Both for traditional attributes and new development, it is clear that these need to be tempered by consideration of risk and performance, and control mechanisms need to be developed to address their application. Three key trends connected specifically with 'green' attributes are the need for renovation of an aging building stock, the presence of new technologies continuously being introduced, and the increased desire to develop a circular economy.

The final dimension of the framework addresses the issue of "Control Mechanisms". These reflect the methods by which democratic societies impose safety provisions on materials, products and systems designed to meet specified societal objectives. In the case of products and services, there is a long tradition of establishing performance requirements through standards or guidelines to define acceptable levels of performance for market accessibility. There are a variety of approaches to the development of control mechanisms, from component testing to end use testing. In the case of many complex products, component testing may be adopted due to the prohibitive cost associated with testing all possible combinations of components in the potential end use. Typical for many control mechanisms is that they include aspects of testing, inspection and compliance over a period of time to ensure that established levels of safety are maintained over time. Unfortunately, such systems are often reactive, with standards being developed as a reaction to incidents or based on the development of innovations which have met the market, but where there are indications that risks might exist even as they remain to be manifest. There is a clear need for such control mechanisms to become more proactive and reflect a socio-technical systems (STS) approach for ensuring fire safety ahead of the curve of development of the product, building or service.

Based on the overview conducted and the analysis undertaken, a set of recommendations for future work to address gaps and to advance the concept of SAFR buildings and communities have been identified.

- <u>Integration of 'green' (sustainable) attributes of buildings into fire incident reporting systems</u>. While more fire incident data are available than was identified in 2012, there remains significant gaps in reporting on fire ignitions and contributions of 'green' building materials, systems and technologies, and how sustainable planning and building features may have impacted the severity of a fire or the response of the fire service. While some major events such as the Grenfell Tower fire capture attention for some time, it may be that there are hundreds of fires involving sustainable building materials, systems (technologies) and features that are not identified, and therefore not available to inform mitigation options.

- <u>More robust and appropriate test methods, which yield engineering data, for assessment of material, component and systems performance.</u> Closely related to the above, while some progress has been made on better understanding fire performance of 'green' attributes of buildings, some of the current standardized testing may not capture the fire safety hazards and risks of the materials, systems and technologies in use (i.e. real life scenarios) well enough. Furthermore, the outcomes of the tests are not always conducive to engineering analysis through computational methods; and given the cost of mid- and full-scale testing, relevant data for the extrapolation or interpolation of results using engineering methods, are not developed. The fire performance of complex façade systems is but one example. Data for engineering analysis is needed for all components, and the means to assess real-scale system performance is required.

- <u>Integration of fire performance considerations into sustainable materials, technologies and features research and development.</u> As emerging technologies such as carbon capture systems, new structural materials, BIPV and more are developed, fire safety needs to be at the front end of the design process, and not an afterthought. Consider what happens as building integrated photovoltaics system (BIPV) technology becomes fulling integrated into façade systems, providing a potential source of ignition that is continuously available. In product design, like building design, the cost to mitigate at the end is much higher than at the outset. This will require a change in thinking within the product and building design communities, although this can build on a tradition of product design for the environment (DoE) adopted in consumer products previously.

- Robust risk and performance assessment methods and tools, which are founded on broad expert stakeholder knowledge and experience, available data, and expert judgment where data are lacking. One could argue that by definition emerging technologies will have many unknowns. While testing, such as component level fire testing, can provide insight into part of the scenario, it may be insufficient to understand the overall fire performance. Risk-informed performance-based methods are needed to provide insight into the range of possible realizations of complex systems designs, and to inform mitigation strategies to control the risks to tolerable levels. Without all of the physical or statistical data needed to make judgements with very small bands of uncertainty, expert judgment, broad stakeholder deliberations, and use of available data will be needed. Methodologies that appropriately integrate these components will be essential.

- Better tools for holistic design and performance assessment, taking advantage of BIM and other technologies that are defining the future of the construction market. Fire safety design is not, and should not, be an isolated practice. Rather, it is part of a holistic design of a building. Better analysis and design tools for support of multi-dimensional performance assessment will be needed, and more use of technologies such as BIM, which are already widely used in the design practice, will be needed. As the industry moves to modular, or prefabricated prefinished volumetric construction, analysis and design decisions will be made 'in the shop' prior to manufacturing of components for shipment to the site and assembled into a finished building. Not only will the design technologies be essential, but also the means to assure the assembled building has addressed key issues, such as fire protection of connections, fire protection of void spaces, and the like. If such a building has issues that need to be 'fixed' after construction, the costs could be significant.

- Transition to more holistic, socio-technical systems approaches for building regulatory systems, which consider the diversity of societal and market objectives for building design, construction and lifetime operation. The current building regulatory system remains largely structured following the 'regulation by event' approach that has been used for the past 100 years. Regulatory development is undertaken largely by disparate experts working in individual silos with the hopes that the outcome is a horse and not a camel. There are numerous societal and market objectives for building design and construction, and there should be requirements for lifetime performance in operation, across a wide spectrum of aspects, including sustainability and fire resiliency. Investigations into fires such as the Grenfell Tower point in some ways to how fortunate we are that catastrophic fire remains a relatively rare event. Evolving the building regulatory system to a more socio-technical systems approach can help better identify and address the diversity of objectives a building is expected to achieve throughout its lifetime. This includes all aspects of the regulatory system, including regulations, standards, compliance, etc.

- Further development and articulation of the SAFR building concepts and its societal and economic benefits. The concept of Sustainable And Fire Resilient (SAFR) structures has been proposed as a way to better integrate sustainability and fire safety performance objectives in building design and performance. A 'green' building is not so 'green' if it burns down and needs to be reconstructed. A fire sprinkler system is not just a life safety system, but is a means to minimize environmental impact should a fire occur. Steps need to be taken to develop concepts that deliver on both objectives in a holistic manner.

Preface

This report has been developed as a collaboration between Meacham Associates and Lund University in response to a request for proposals developed by the Fire Protection Research Foundation (FPRF). The findings are based on an information review conducted by the authors and input from the FPRF Project Technical Panel (PTP) and FPRF Property Insurance Research Group (PIRG).

The PTP is comprised of the following members:
Francine Amon, RISE
David Barber, Arup
Anthony Hamins, NIST
Amanda Robbins, NRC Canada (invited)
John Shafer, Washington Twp./Avon (Indiana) Fire Department
Debbie Smith, BRE (invited)
Ray Walker, IFMA Representative
Peter Weismantle, Adrian Smith + Gordon Gill Architecture LLP
Val Ziavras, NFPA staff liaison

The PIRG is comprised of several individuals from the following organizations:
AIG
CNA
FM Global
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Tokio Marine
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Zurich

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Shrewsbury, MA, USA, October 2020.

Table of Contents

List of Figures

List of Tables

Acronyms, Abbreviations and Selected Definitions

Attributes	In this report, attributes is a high-level term that includes materials, systems (technologies) and features.
Conventional buildings	In the context of this report, the term "conventional buildings" or "conventional construction" is synonymous with "traditional buildings" or "traditional construction," which has been preferred in this report. The two are synonymous, see "traditional buildings" for a definition.
Green (sustainable) buildings	There are many definitions of 'green' buildings. For the purpose of this report, we adopt the World Green Building Council (WBGC) definition: "a 'green' building is a building that, in its design, construction or operation, reduces or eliminates negative impacts, and can create positive impacts, on our climate and natural environment. 'green' buildings preserve precious natural resources and improve our quality of life." Single quotes around 'green' indicates that the word is being used to denote 'sustainable' buildings or attributes, rather than the colour green.
Resilient	There are many definitions of resilient (or resiliency). As used in this report, it is defined as the ability to prepare and plan for, absorb, recover from, and more successfully adapt to adverse events.
Resilient buildings	Resilient buildings are those which are designed for long life. Resilience can be achieved in many ways, from use of durable and highly reliable components, to ease of repair and renovation, to high level of resistance to expected hazard impacts. Attributes can include reduced susceptibility to single points of failure, increased robustness, redundancy and reliability of systems and components, and flexibility and adaptability.
SAFR	Sustainable And Fire Resilient
SAFR buildings	SAFR buildings (structures) are those which are designed to both be sustainable in terms of reducing or eliminating negative impacts on our climate and natural environment, and resilient in terms of their ability to safeguard people, property, operations and the environment from unwanted fire.
Sustainable	There are many definitions of sustainable (or sustainability). As used in this report, it is defined as responsibly interacting with the planet to maintain natural resources and avoid jeopardizing the ability for future generations to meet their needs.
Traditional buildings	Refers to buildings constructed using materials, systems and features that preceded the focus on 'green' or sustainable attributes. Generally, but not exclusively, this refers to building materials, systems and features widely in use prior to the 1980s, when 'green' building concepts significantly emerged.

1. Introduction

1.1 Background

In 2012, the Fire Protection Research Foundation (FPRF) supported the project, *Safety Challenges of Green Buildings*, the objectives of which were to a) systematically document a set of 'green' building design elements that may increase fire safety hazards, and, b) share best practices identified via the search with respect to fire hazard risk mitigation associated with 'green' building design elements. The work was conducted by carrying out a global literature search to:

i. Identify documented fire incidents in the built inventory of 'green' buildings.
ii. Define a specific set of elements in 'green' building design, including configuration and materials, which, without mitigating strategies, increase fire risk, decrease safety or decrease building performance in comparison with traditional construction.
iii. Identify and summarize existing best practice case studies in which the risk introduced by specific 'green' building design elements has been explicitly addressed.
iv. Compile research studies related to incorporating building safety, life safety and fire safety as an explicit element in 'green' building indices, identifying gaps and specific needed research areas.

The project was carried out and a final project report was published (Meacham et al., 2012). This effort identified more some 80 'green' (sustainable) building materials, systems and features and 22 potential sources of increased hazard or risk associated with the 'green' materials, systems and features. The work combined the 'green' building materials, systems and features and potential sources of increased hazard or risk as a 'relative risk matrix' and presented the information in tabular format as qualitative representations of the potential 'additional' hazard or risk presented by the 'green' buildings materials, systems and features. The outcomes were well received, spawning related research (e.g., Meacham et al., 2017) and several derivative publications and presentations.

In the eight years since the project report was published, there have been several major fire events, which involved 'green' building features or technologies, including numerous high-rise exterior façade fires around the world, notably the Grenfell Tower fire in London (combustible insulation), the Dietz & Watson cold storage warehouse in Delanco, New Jersey (photovoltaic panels, combustible insulation), and a spate of fires in buildings under construction using lightweight timber framing. While each of these can be categorized in many ways, they (and many others) include materials, systems (technologies) and features that are considered 'green' or sustainable (collectively referred to as 'green' building attributes). There has also been new research and some regulatory change. This work presented in this report represents a review of how the situation with safety challenges of 'green' building features and technologies has developed since the end of 2012.

It should be noted that while some areas addressed in 2012 are again highlighted here (e.g., photovoltaic systems and mass timber construction), this is largely related to increased use and/or more regulations or guidance. In other cases, such as the benefits of sprinklers as a 'green' (sustainable) attribute, are not reiterated here (see the 2012 report for more on sprinklers).

1.2 Use of 'Green' Buildings in this Report

'Green' buildings mean different things to different people. According to the World Green Building Council (WBGC), "a 'green' building is a building that, in its design, construction or operation, reduces or eliminates negative impacts, and can create positive impacts, on our climate and natural environment. 'Green' buildings preserve precious natural resources and improve our quality of life."

Efforts to facilitate 'green' or sustainable building design can be traced back to the launch of the first 'green' building assessment method in 1990 (BRE, 1990). The US Green Building Council followed in 2000 with the launch of the LEED system (USGBC, 2000). Since the establishment of these systems, others have followed and continue to be developed. In this project, the concept of a 'green' building and/or 'green' building materials, systems and features has not been restricted to those that have been awarded a particular certificate to signify their 'greenness' but has broadly included the concept of any building designed with sustainability in mind.

This broad definition means that not only buildings that can seek one of the common 'green' building certificates, or are designed as 'green' according to the definition of the WGBC or other such rating scheme, are included. More broadly, this definition applies to both new buildings with at least some 'green' attributes, as well as to existing buildings which incorporate 'green' attributes during renovation.

1.3 Project Aim

This project aims to conduct a global information search into fire events involving 'green' and/or sustainable building materials, systems and features, and into research, regulatory changes, engineering approaches, risk mitigation strategies, and firefighting tactics associated with fire challenges with 'green' and/or sustainable building materials, systems and features, which have emerged since the publication of the 2012 report, *Fire Safety Challenges of Green Buildings* (Meacham et al., 2012).

1.4 Project Tasks

The project is divided into the following main tasks:

Task 1. Identify documented fire incidents involving 'green' and/or sustainable building materials, systems (technologies) and features.

Task 2. Review, update and modify as deemed appropriate the list of 'green' and/or sustainable building materials, systems and features identified in the 2012 report, which, without mitigating strategies, potentially increase fire risk, decrease safety or decrease building performance in comparison with traditional construction.

Task 3. Identify and summarize existing best practice case studies in which the risk introduced by specific 'green' and/or sustainable building materials, system and features have been explicitly addressed.

Task 4. Update the list of research studies related to incorporating building safety, life safety and fire safety as an explicit element in 'green' building indices, identifying gaps and specific needed research areas that might still exist.

1.5 Limitations

This project is largely an 'information survey' undertaken to extend the understanding of the current state of knowledge regarding the potential fire safety impacts of 'green' / sustainable building materials, systems and features since the original FPRF report on this topic from 2012 (Meacham et al., 2012). While the intent is to take a broad view of the issues, it is not practicable to be exhaustive in scope or level of detail, within the resource constraints of the project. As such, the focus is on presenting representative information on the subject as a means to help identify the current situation and where future research could be beneficial. Further, while the literature presented is extensive (over 400 references), the risk assessment methodology itself has not been changed, only the 'green' attributes included have been expanded, and (in some cases) the potential level of risk (low, moderate or high) has been updated.

In many cases, the fire performance of emerging 'green' attributes is yet to be established as few fire events have been reported. Therefore, some of the discussion of fire safety challenges is necessarily speculative. Only time will tell whether our informed speculation will bear true.

It is also important to note that the potential fire safety impact of 'green' attributes may be a function of specific building characteristics, such as height, volume of materials used, etc. It is not possible to address all the permutations and combinations of potential fire hazards and risks associated with the range of 'green' attributes and building characteristics in this informational review. Rather, the focus is on characteristics of the 'green' attributes of concern, and potential risks and hazards, and assessment of specific conditions for a building are necessarily left to those working on the design of specific buildings. Also, while a review of changes to regulations, standards and guidance is provided, it is not the intent of this work to recommend specific changes, but again, to highlight potential issues for consideration. It is anticipated that those involved in the building design process understand well the fire safety objectives for buildings, how they might change with varying building characteristics, and how they are addressed in building regulation, and make informed decisions based on the information such as provided in this overview.

All research, summaries, opinions, findings, conclusions and recommendations expressed in this report are those of the authors and do not necessarily reflect those of the FPRF, the PTP, the PIRG, the NFPA or other sponsors, institutions, agencies or organizations which have supported this research. Any reference to specific materials or systems is provide solely as examples and should not be construed as an endorsement of said materials, systems or technologies by the authors, the FPRF, the PTP, the PIRG, the NFPA or other sponsors. While reasonable care has been taken by the authors to accurately reflect the information and sources contained within this work, it may be that some errors exist. The authors will take steps to rectify any such errors in reporting that are brought to their attention.

1.6 Project and Report Structure

To guide the research, analysis and presentation of outcomes associated with the tasks stated above, the project was structured in a series of steps, for which chapters of this report were developed, as illustrated in Table 1.1.

Table 1.1: Description of Project Steps and Report Structure

STEP	*CHAPTER*
Step 1: *Literature review methodology*	Chapter 2: Review Methodology
Step 2: *Review the literature (scientific, media reports, and where publicly available, investigation reports), to develop a contemporary list of fire and safety events that have involved 'green' and/or sustainable building materials, features and technologies*	Chapter 3: Fire Incidents
Step 3: *Review the scientific literature, including journals, university and research reports, related to studies that have been undertaken related to fire challenges of 'green' / sustainable building materials, features and technologies since 2012*	Chapter 4: Scientific Studies
Step 4: *Review the 2012 categorization of 'green' / sustainable building materials, features and technologies, and the 2012 list of fire and life safety hazards and risks of concern, and update / revise if appropriate*	Chapter 5: 'Green' Attributes and Potential Fire Hazards
Step 5: *Review and update the 'first-order' hazard / risk assessment framework presented in the 2012 report, and provide an updated perspective on a framework or approach that allows for systematic assessment and documentation of 'green' building design elements with an impact of fire safety*	Chapter 6: Relative Hazard / Risk Assessment Frameworks
Step 6: *Consideration of whether / how the concept of 'resiliency' may be an opportunity for facilitating 'safe and sustainable' buildings, and if so, whether risk assessment and management techniques associated with resiliency objectives might be helpful*	Chapter 7: Resiliency
Step 7: *Search the literature for regulatory changes associated with fire challenges of 'green' / sustainable building materials, features and technologies which have been undertaken since 2012*	Chapter 8: Regulations and Guidance
Step 8: *Compile information obtained with respect to firefighting tactics.*	Chapter 9: Firefighting Tactics
Step 9: *Identification of gaps that remain, new challenges that exist, and areas where future research and development*	Chapter 10: Analysis and Research Needs
Step 10: *Summarize and identify future research needs.*	Chapter 11: Conclusions and Future Work

2. Review Methodology

The information review presented in this report was based on the following approach:

1. Review of the 2012 report *Safety Challenges of Green Buildings* (Meacham et al. (2012) with respect to search parameters, sources cited and findings.
2. Use of various general search engines (e.g., Google, Bing, etc.) and the IAFSS Fire ReSearch Engine (https://iafss.org/fire-research-engine/) for fire incidents and events, reports published in the open literature, media reports, and the like.
3. Literature search based on a selection of search strings in the LUBsearch function offered by the Library at Lund University. Snowballing from identified references to flesh out specific topics. (The full list of databases included in this search function is found in Appendix 1.)
4. Review of specific research report outlets, such as the FPRF website, outreach to researchers in the field (e.g., at UL), and outreach to, and feedback from, the Project Technical Panel and Property Insurance Research Group.

Searches included the words "fire", "incident", "risk", "hazard", "performance" and "regulations" in the string supplemented by the following.

- "green buildings"
- "sustainable buildings"
- "green building technology"
- "sustainable building technology'
- "sustainable construction"
- "façade systems"
- "exterior wall system"
- "green walls"
- "green roofs"
- "thermal insulation"
- "photovoltaic systems"
- "PV systems"
- "building integrated photovoltaics"
- "BIPV"
- "energy storage systems"
- "ESS"
- "mass timber"
- "CLT"
- "sustainable building technology trends"
- "emerging trends sustainable building technology"
- "resilient construction"
- "sustainability and resiliency"
- "sustainable planning and development"

As part of these searches, more than 400 sources have been identified and reviewed to some extent. The results of the searches have been grouped according to which design feature they mainly relate to. While the searches were extensive, they are not necessarily exhaustive, given the volume of information and limits on the project. The searches and reviews therefore reflect representative data. In many cases there are extensive publications available for each aspect addressed in this report. Therefore, review articles have been chosen when available, as a starting point for the interested reader to obtain an introduction to a research area pertaining to a specific material, system or feature. The reader is then encouraged to track the area if more detail is needed by searching references in the review articles.

3. Fire Incidents

3.1 Fire Incident Data Collection

To obtain a good sense of the extent of fires involving 'green' or sustainable materials, systems and features (attributes) of buildings, it would be helpful to have robust fire incident data. This was identified as a need in 2012 (Meacham et al., 2012), when it was reported that "there are currently no fire incident reporting systems in the United States or other countries surveyed which specifically collect and track data on fire incidents in 'green' buildings or on items labeled as 'green' building elements or features. Unless changes are made to reporting systems such as NFIRS, it will be difficult to track such fire incident data." This was echoed in a derivative research effort, which looked more closely into data that could perhaps be collected through the National Fire Incident Reporting System (NFIRS) in the USA, which identified only a handful of reported incidents, and suggested changes to NFIRS that could help to facilitate more extensive data collection in this area (Meacham et al., 2014; You et al., 2014; 2017). Unfortunately, only limited progress seems to have been made as part of formal fire incident reporting, supplemented by some targeted studies.

3.1.1 Fire Incident Reporting of 'Green' Building Attributes in the USA as of 2014

As part of a U.S. Department of Homeland Security (DHS), U.S. Fire Administration (USFA), funded project that aimed to quantify the impact of 'green' building features on firefighter safety, one research area explored the extent to which formal fire incident data collection systems in the USA captured fires involving 'green' or sustainable building features, attributes and technologies (Meacham et al., 2014; You et al., 2014; 2017). Since the highest percentage of fires and firefighter injuries and deaths is related to residential buildings, that was the primary focus.

One aspect of this research explored data reported to the National Fire Incident Reporting System (NFIRS) database. Details on NFIRS and data challenges are not discussed here but can be found elsewhere (e.g., Kinsey and Ahrens (2016); NFIRS (2020)). However, it should be noted that NFIRS does not include a 'green' building taxonomy, so focus was given to identified 'green' building materials, systems and features as identified in Meacham et al. (2012). The NFIRS database yields two types of data: those data populated by fire incident data collected by fire departments across the country (raw data), and estimates made by combining the raw data with data from the National Fire Protection Association's (NFPA's) annual *Survey of Fire Departments for U.S. Fire Experience* to estimate the total number of fires in the USA (national estimates). Table 3.1 reflects a summary of NFIRS from 2007 to 2011 in which incidents of residential structural collapse involving 'green' building features was targeted (You et al., 2014). In this effort, 'green' building features and structural collapse were targeted from NFIRS Fire Suppression Factors, which are factors that could directly impact the ignition, fire spread, incident complexity, and hazardous conditions.

Table 3.1 NFIRS Data Collection based on Raw Data and National Estimates (2007-2011)

Fire Suppression Factors Code	Factors Related to Green Building Features	Incidents having this Factor: Raw Data	Incidents having this factor: National Estimates	Total Incidents
182	Composite plywood I-beam construction	19	100	42
183	Composite roof/floor sheathing construction	32	149	N/A
185	Wood truss construction	267	1333	N/A
186	Metal truss construction	3	20	N/A

Because NFIRS does not include a 'green' building attribute taxonomy, and the terminology of the Fire Suppression Factors encompass broad typologies, it is not always possible to parse 'green' construction from other. For example, the Fire Suppression Factor "Wood Truss Construction" can include both "traditional" wood construction and "lightweight" wood construction." These limitations significantly hamper the benefit of NFIRS in identifying fires involving 'green' building features, elements and technologies. Also, while "solar panels" was added to fire suppression factors, firefighters have to remember it exists, and if they skip fire suppression factors altogether, the specific data element may not identified or recorded.

In addition to NFIRS data, this effort also explored a statewide fire incident data set, specifically the Massachusetts Fire Incident Reporting System (MFIRS, 2020). MFIRS is a reporting system maintained by Commonwealth of Massachusetts that is quite similar to NFIRS. While MFIRS captures 'solar panels' as a data point, unfortunately (or fortunately), no solar panel fires had been reported at the time of the cited study. Table 3.2 reflects the data collection summary for MFIRS from 2001 to 2013.

Table 3.2 MFIRS Data Collection Summery (2001-2013)

Fire Suppression Factor Code	Factor related to 'Green' Building Attributes	Incidents having this Factor	Incidents also having Structural Collapse	Incidents are also Residential Property	Total Target Incidents
115	Solar Panels	0	0	0	0
182	Composite plywood I-beam construction	6	2	1	1
183	Composite roof/floor sheathing construction	21	1	0	0
185	Wood truss construction	40	8	3	3
186	Metal truss construction	6	1	0	0

Lastly, the Fire Incident Data Organization (FIDO) was explored. FIDO is operated and maintained by NFPA. It varies from NFIRS and MFIRS in that FIDO only collects selected incidents: fatal, designated large loss, or sprinklers are activated. The advantage of FIDO is that detailed information of the incidents is collected and can be obtained from NFPA's Fire Analysis & Research Division. Table 3.3 illustrates the number of residential green building fires each year from 2003-2013 as determined based on FIDO data. The target incidents are Residential Structural Collapse Incidents Involving 'Green' Building Attributes.

Table 3.3 FIDO 'Green' Residential Structural Collapse Fires Collection Summery (2003-2013)

Year	Residential Collapse Fires	Identified 'Green' Building Fires
2013	28	1
2012	48	1
2011	50	3
2010	46	1
2009	52	3
2008	58	1
2007	41	2
2006	34	3
2005	19	0
2004	20	0
2003	15	0
Total	411	15

It is worth noting that in Table 3.3, the number of 'suspected' fires in buildings with 'green' attributes is greater than the number of 'identified' ones. This is because it is difficult to extract verifiable 'green' building attributes from the incident details, i.e., the detailed information about 'green' attributes are not captured.

However, because more detailed data are provided, it is possible to extract 'green' building attributes from some incidents. A more detailed set of data, as extracted from FIDO, is presented in Table 3.4. From this analysis, the following 'green' attributes were applied: Structural Materials and Systems – Lightweight Engineered Wood, Lightweight Concrete and FRP elements; Exterior Materials and Systems – Solar Roof Panels and Insulated Vinyl Siding; and Modular Home.

Table 3.4 Identified FIDO 'Green' Residential Structural Collapses Incidents Details

Year	Property Use	Year Built	'Green' Building Attributes	Structural Collapse	FF Injuries	FF Fatalities
2013	Single Family	1989	Solar panels, Wind spires	Roof	0	0
2012	Single Family	1977	Lightweight Wood	Roof	0	0
2011	Single Family	New	Large Void Space, Lightweight Wood, FRP	Ceiling	12	1
2011	Multi APTs		Lightweight Wood	Roof	0	1
2011	Multi APTs		Lightweight Concrete	Floor	2	0
2010	Multi APTs		Lightweight Wood, Insulated Vinyl Siding	Floor	7	0
2009	Multi APTs		Lightweight Wood, OSB	Roof	0	0
2009	Multi APTs	1999	Lightweight Wood	Roof	2	0
2009	Single Family		Lightweight Wood	Floor	3	0
2008	Modular	2005	Modular Home	Roof	0	0
2007	Single Family	2004	Lightweight Wood	Floor	3	1
2007	Single Family		Lightweight Wood, Insulated Vinyl Siding, OSB	Roof	1	1
2006	Single Family	2004	Lightweight Wood, Insulated Vinyl Siding	Floor	3	1
2006	Single Family	1999	Lightweight Wood	Floor	2	1
2006	Single Family		Lightweight Wood	Floor	0	0

For the time period considered in this research, thousands of fire incidents were captured within the NFIRS, MFIRS and FIDO datasets. However, the research team was only able to identify 58 residential fires that likely involved 'green' building attributes. While this could mean that 'green' building attributes are not a fire concern, reports in the media about fires involving solar panels and other 'green' technologies led the research team to conclude that it was more likely that there are many more fires involving 'green' building attributes than identified, however, such fires could not be identified because the reporting systems were not set up to capture 'green' building attributes. Also, narratives are not included in the public NFIRS data set due to privacy concerns. If narratives were available for review, more would probably have been found. In addition, NFIRS reports are often not updated after investigations, so even as additional information may be learned, it may not be reported or recorded. Finally, it could simply be a function of not having reached yet a critical mass.

As a result of this research, several recommendations were made regarding potential changes to NFIRS, MFIRS and FIDO to better collect 'green' building features, attributes and technologies. These included:

- development of a "Green Building Fires Reporting Form", with sections for property information including the year the building was built and renovated and time of structural collapse;
- introduction of 'green' building features, attributes and technologies terminology into NFIRS, FIDO and other systems, such as "lightweight engineered lumber" to capture 'green' technologies, and
- modify the systems to the level of detail required, such as changing "wood frame" into sub categories such as "heavy timber," "lightweight traditional timber," "lightweight engineered lumber", etc.

3.1.2 Fire Incident Reporting of 'Green' Building Attributes in the USA as of 2020

To explore what changes might have been implemented in the fire incident reporting systems since 2012, and to assess the current data reporting situation, the research team reached out to NFPA research and analysis staff for assistance. We greatly appreciate the time, effort and feedback provided by Birgitte Messerschmidt, Marty Ahrens, Rita Fahy and Nancy Schwartz in this regard.

With respect to NFIRS, **Suppression Factor 115 - Solar Panels**, was added to the optional fire suppression factors data element, effective with the 2012 data. Ideally, this new code could yield quite valuable information. However, as noted by NFPA staff, this data field is unfortunately rarely completed. This was not unexpected, and is consistent with overall challenges in obtaining comprehensive input data into NFIRS (e.g., see Kinsey and Ahrens (2016)). An initial run of the raw NFIRS data related to **Suppression Factor 115 – Solar Panels** yielded a total of 73 incidents from 2013 through 2018. The data are presented in Table 3.5.

Table 3.5 NFIRS Raw Data - Suppression Factor 115 – Solar Panels, 2013-2018

Alarm Year	Number of Fires	PCT	Civilian Fatalities	PCT	Civilian Injuries	PCT	Dollar Loss	PCT
2013	8	11.0%	0	0.0%	0	0.0%	$1,973,000	20.0%
2014	8	11.0%	0	0.0%	0	0.0%	$323,850	3.3%
2015	9	12.3%	0	0.0%	0	0.0%	$1,566,500	15.9%
2016	19	26.0%	0	0.0%	1	100.0%	$1,818,600	18.4%
2017	17	23.3%	0	0.0%	0	0.0%	$2,439,800	24.7%
2018	12	16.4%	0	0.0%	0	0.0%	$1,760,000	17.8%
TOTALS	**73**	**100.0%**	**0**	**100.0%**	**1**	**100.0%**	**$9,881,750**	**100.0%**

While more data than was found in 2014, the numbers are still low. Also, as reported in 2014, there is insufficient information associated with the data to understand context (e.g., associated with building, or part of a solar array field).

NFPA staff also explored the NFIRS data as associated with 'equipment power source.' This includes various fuels and power sources, including **code 54 – wind**, **code 55 – solar**, and **code 56 – geothermal**. It also includes batteries, but under **code 12 – batteries and low voltage (< 50 volts)**, which would not include larger battery / energy storage systems (ESS). An initial run of the raw NFIRS data related to **Equipment Power Source 55 – Solar** yielded a total of 128 incidents from 2009 through 2018. The data are presented in Table 3.6.

Table 3.6 NFIRS Raw Structure Fire Data for Equipment Power = 55-Solar by Year

Alarm Year	Number of Fires	PCT	Civilian Fatalities	PCT	Civilian Injuries	PCT	Dollar Loss	PCT
2009	6	4.7%	0	0.0%	0	0.0%	$46,100	0.8%
2010	2	1.6%	0	0.0%	0	0.0%	$500	0.0%
2011	7	5.5%	0	0.0%	0	0.0%	$901,810	16.2%
2012	11	8.6%	0	0.0%	0	0.0%	$550,000	9.9%
2013	19	14.8%	0	0.0%	0	0.0%	$639,052	11.5%
2014	11	8.6%	0	0.0%	0	0.0%	$339,600	6.1%
2015	8	6.3%	0	0.0%	0	0.0%	$401,000	7.2%
2016	14	10.9%	0	0.0%	0	0.0%	$420,455	7.5%
2017	21	16.4%	0	0.0%	0	0.0%	$1,663,132	29.8%
2018	29	22.7%	0	0.0%	0	0.0%	$611,250	11.0%
TOTALS	128	100.0%	0	100.0%	0	100.0%	$5,572,899	100.0%

While the data suggest 128 fire incidents, there is insufficient information associated with the data to understand context (e.g., associated with building, or part of a solar array field).

Another database that was queried by NFPA staff is the NFPA clip service, which searches media reports. Here again, an initial assessment searching on 'solar panels' was made. This search yielded some results, for which a small number had associated fire department reports. Those reports, however, are confidential. Incidents identified through the clip service, that have associated fire department reports, are presented in Table 3.7.

Table 3.7 Fire Incidents Involving Solar Panels from Clip Service

Incident	Building Type	Comments
09-02263	dwelling	Brief article available "Simi solar panel fire raises safety issue"
09-02065	department store	As of April 2020, information (article) available online at http://media.iccsafe.org/news/eNews/2009v6n10/target.pdf
12-00776	school	Brief article available "solar panels malfunction"
12-01546	dwelling	According to the report, the fire started where conduit from solar panels went into the house
13-01327	department store	According to the report 'the wiring from underneath solar panel had melted and dropped onto roof covering. Thus, causing roof material to ignite and spread when wind was blowing'

As a result of the initial search on the data for solar panels in the NFIRS system, it was determined that the NFIRS database would not yield sufficient data for analysis, so it was decided to not explore in more detail as part of this effort. The same decision was made with respect to FIDO. It is also noted that the clip service is capturing events, but often detail that might be helpful to understand the contribution of the 'green' element is missing.

With respect to fire incident data reporting in the USA, while gains have been made since 2012, including the addition of some data fields to NFIRS, the data is not consistently or fully being reported. Also, while more events are now captured by the clip service, helpful details are often missing. Overall, this points to the need to again recommend future efforts associated with fire incident data collection for 'green' building features, attributes and technologies.

3.1.3 Fire Incident Reporting of 'Green' Building Data Outside of the USA

PV Systems - Germany

A paper on fire incidents in solar panels in Germany was presented at the 28th European PV Solar Energy Conference and Exhibition held in Paris in 2013 (Laukamp et al., 2013). The data were collected as part of a project to identify and address issues with photovoltaic (PV) system safety and reliability, fire protection, building code related issues, and firefighter safety. Fire incidents involving PV systems in Germany for the period 1995 through 2012 were reviewed.

Of the some 400 fire incidents identified, it was determined that a PV system caused 179 of the fires. Of these fires, 10 resulted in complete building destruction, 65 resulted in building damage, 49 resulted in damage to the entire PV system, and 55 resulted in damage to only some components of the PV system. Interestingly, the majority of fires were caused by PV systems installed on roofs with standoff systems. This is reflected in Figure 3.1, redrawn from Laukamp et al. (2013).

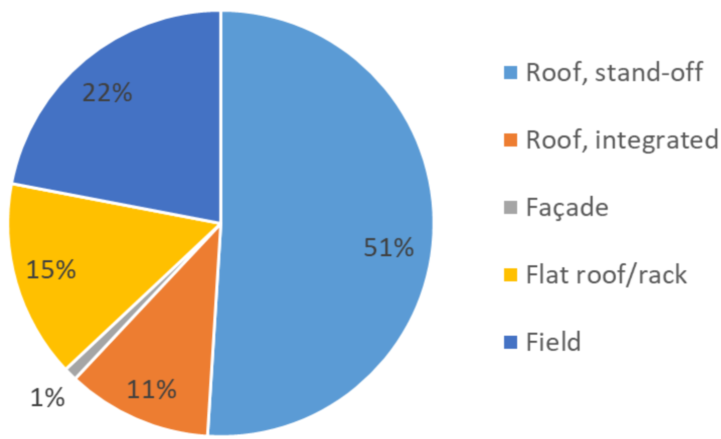


Figure 3.1 Distribution of PV System Fires by Mounting Type (Laukamp et al., 2013)

The study explored several contributing factors, including product defect, planning/design fault, installation fault and external influence. There are summarized in Figure 3.2, redrawn from Laukamp et al. (2013).

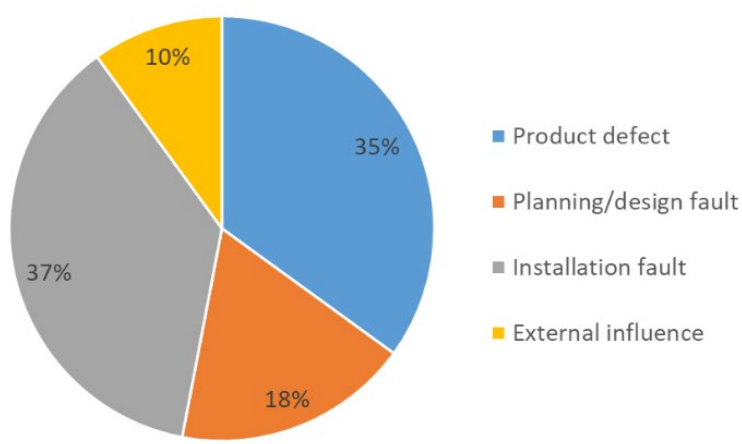


Figure 3.2 Distribution of Identified Causes of Fire (Laukamp et al., 2013)

With respect to when fires occur, as a function of overall time in operation, the data suggest a large majority fail within the first year (Figure 3.3, redrawn from Laukamp et al. (2013))

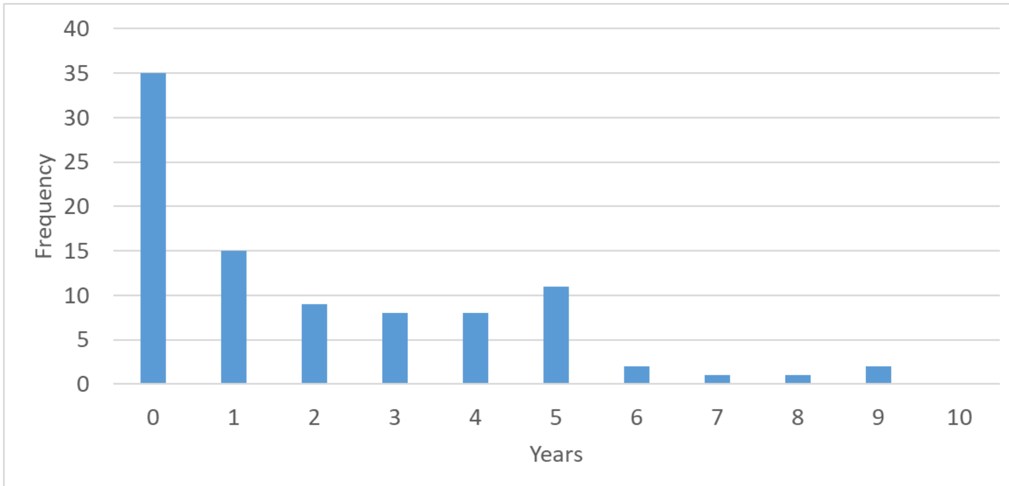


Figure 3.3 Number of Incidents Over Operating System Age (Laukamp et al., 2013)

The data from this study also shows an increasing number of fires per year (Figure 3.4, redrawn from Laukamp et al. (2013)), noting that the increase correlates well with German data on installed capacity per year.

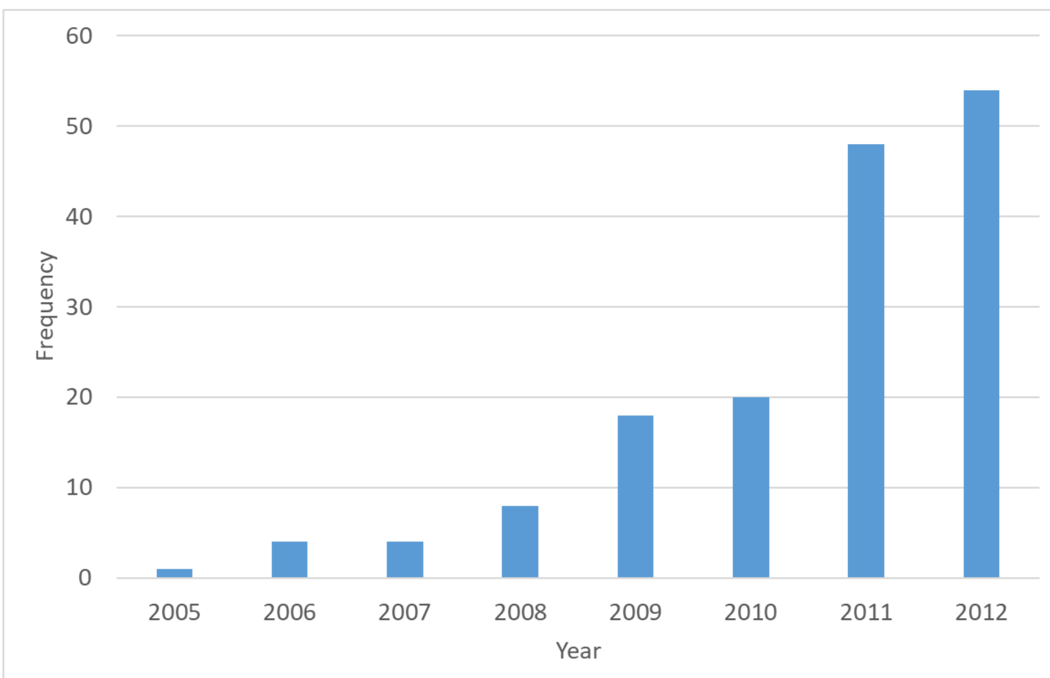


Figure 3.4 Number of Incidents Per Year (Laukamp et al., 2013)

Considering the number of damaged buildings in q year, and relating it to the number of installed PV systems in Germany, an annual risk of approximately $3*10^{-5}$ that a building is damaged due to a fire caused by its PV system was estimated.

In many respects, as with the USA data discussion above, incident data collection on such systems is in the early days. With respect to Figure 3.3, over time, one might expect to see a 'bathtub' curve, wherein number of incidents might start to increase again towards the end of product lifecycles, as parts wear out and perhaps maintenance is less than optimal. Such a potential outcome could be mitigated somewhat by regulatory and technology changes over time (e.g., reliability is better, fire protection is better) if so implemented.

PV Systems - Italy

A paper on fire challenges with photovoltaics in Italy was presented at the 33rd European Photovoltaic Solar Energy Conference and Exhibition (Bonomo et al., 2017). The paper presents results from a survey of the Italian National Fire Rescue and Service (CNVVF) which found that around 2500 fire related accidents have occurred in the nearly 550,000 PV systems currently installed in Italy during the period 2002 through 2015. While not explicitly stated, it is assumed this number reflects PV systems integrated with buildings, as that is the general focus of the research. This reflects roughly a fire in 0.45% of installations overall. Picking a particular year, such as 2012, the annual frequency (assuming 555,000 systems) is about $8.7*10^{-4}$. The yearly incident totals are reflected in Figure 3.5 (redrawn from Bonomo et al. (2017)).

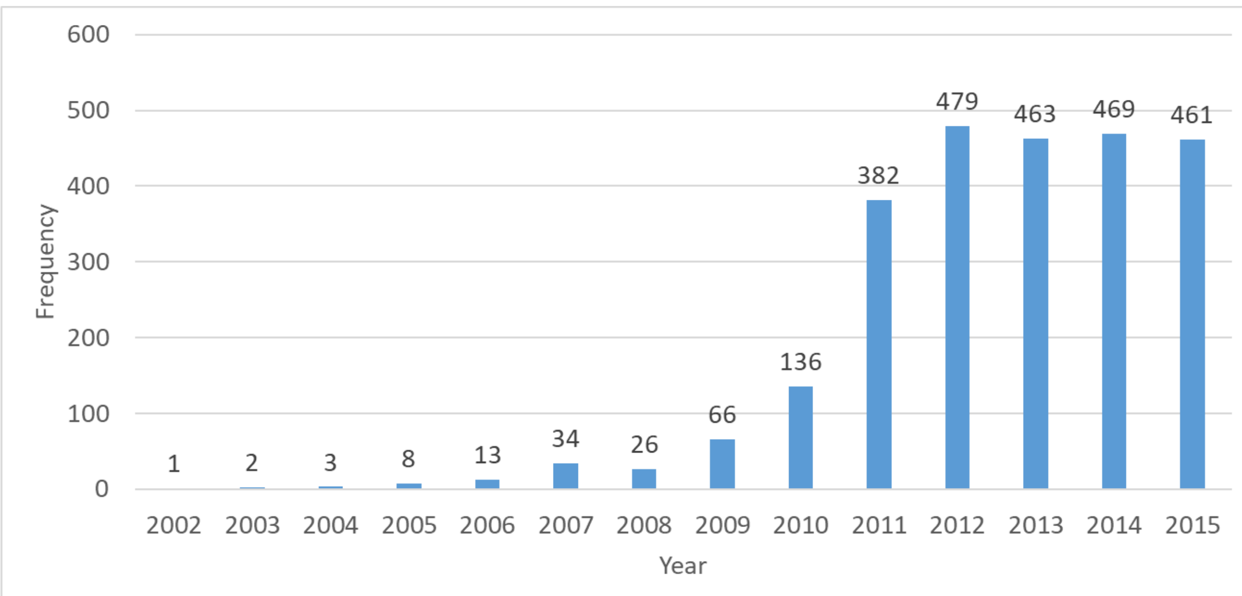


Figure 3.5 Fire Incidents in PV Systems in Italy by Year, 2002-2015 (Bonomo et al., 2017)

As reported in the paper, the potential sources of the PV system fires in Italy, excluding power converters as a possible source, are presented in Table 3.8 (reproduced from Bonomo et al. (2017)). They are grouped generally as 'localized over heating' and 'electric arc faults'.

Table 3.8 Potential Sources of PV System Fires in Italy (Bonomo et al., 2017)

Potential Fire Source	Effects
Unprotected hot spots at module level	Localized over heating
Faulty or undersized bypass diodes	
Poor electrical insulation of the PV circuit to under-construction and/or ground	Electric ARC fault (parallel)
Poor or neglected wiring and insulation of wiring harness	
Poor electrical interconnections and bonding cell-to-cell (module level)	Electric ARC fault (series) or localized over heating
Faulty connectors (module-to-module)	
Faulty electrical connections inside the junction boxes	

It is interesting to note a leveling off of fire incidents with time. However, data are not provided to determine whether this correlates with total installations, or if other factors are at play.

PV Systems - United Kingdom

A research project was undertaken by BRE National Solar Centre, Ltd. and the BRE Global Fire Safety Group, on behalf of the UK Department of Energy and Climate Change, that investigated historical and contemporary fire incident data and research regarding PV systems and fire (Coonick and Bregulla, 2018). The aim of the project was to provide data for support of industry standards, the National Occupational Guidance system, and for dissemination to the fire and rescue services.

Several tasks were undertaken as part of this project, including:

- A review of the literature
- A review of standards
- Development of a database on fire incidents involving PV systems
- Site investigations and desk studies of contemporary incidents (i.e., during project)
- Publication of outcomes

A full set of published reports is available at https://www.gov.uk/government/publications/fire-incidents-involving-solar-panels (accessed February 2020) (GOV.UK, 2017).

Of particular interest to this section of the FPRF study report is the database of fire incidents involving PV systems (Coonick and Bregulla, 2018). A total of 80 fire incidents were identified as part of the BRE project, which represents a fire in approximately $1*10^{-4}$ (0.01%) of the PV system installations in the UK as of 2018. A breakdown of incident severity and PV system involvement is provided in Table 3.9 (reproduced from Coonick and Bregulla (2018)). Note that while the reports do not explicitly state that the data are for PV systems installed on buildings, it appears that much of the data reflect such incidents, given the taxonomy selected and discussion in the report on inspection and investigation parameters.

Table 3.9 Summary of Fire Severity and PV System Involvement (Coonick and Bregulla, 2018)

Severity of Fire	Caused by PV	Involving but not caused by PV	Cause Unknown	Total
Serious Fires	22	15	1	38
Localized Fires	27	1	5	33
Thermal Events	9	0	0	9
Total	**58**	**16**	**6**	**80**

The severity of the fire was classified based on the following taxonomy:

- Serious fires were difficult to extinguish and spread beyond the area of origin
- Localized fires caused some damage to areas surrounding the point of origin, mainly affected PV system components, but did not spread beyond that or threaten the building
- Thermal events consisted of components that over-hearted, often observed to be smoldering or producing smoke, but did not develop into a flaming fire

Data was obtained from assessment of 'historical' events (events which occurred before the study began) and site investigation of contemporary events (events which occurred during the study period). A total of 33 historical events were identified through contact with PV industry personnel and fire service personnel, query of the Department of Housing and Local Government (DHLG) Incident Reporting System (IRS), and internet searches. As in the USA, it was noted that the IRS tended to contain little technical detail on PV-related events. A total of 21 site investigations were conducted. These included fires at:

- 10 dwellings
- 4 commercial buildings
- 2 residential homes
- 2 leisure centers
- 1 school
- 1 industrial building, and
- 1 ground-mounted system

As with the studies overviewed above, the UK study looked at root causes of the fires, identifying the following general factors as presented in Table 3.10 (reproduced from Coonick and Bregulla (2018)).

Table 3.10 General Interpretation of Root Cause of Fires (Coonick and Bregulla, 2018)

Root Cause	Probable	Possible Further
System design issue	6	3
Faulty product	3	10
Poor installation	21	2
Unknown	28	0
N/A (fire not caused by PVS)	22	0
Total	**80**	

Façade Systems – Global

A building façade fire incident database has been developed with support from the Council on Tall Buildings in the Urban Habitat (CTBUH) and Sun Hung Kai Properties (Spearpoint et al., 2019). The dataset includes 59 incidents from 21 countries, as identified in studies by Wade and Clampett (2000), White and Delichatsios (2014), Valiulis (2015) and Evans (2016)and supplemented with further incidents identified through web-based searches and other resources.

Database input fields include (Spearpoint et al., 2019):

- Building configuration: height/number of stories above ground; construction material; geographic location; years of completion and renovation if applicable; and whether a sprinkler system was present.
- Relevant fire incident parameters: reported cause of the fire; where fire started in relation to the façade (for example, whether the fire originally started inside the building before spreading to the façade or whether the incident was the result of an external fire, such as the burning of rubbish, etc.); on what floor the façade initially became involved; any wind effects; and whether there was reported manual intervention (i.e., fire service) or sprinkler system activation.

Analysis of the dataset was undertaken and outcomes are presented, including materials within the façade systems that burned (Figure 3.6, as reproduced from Spearpoint et al. (2019)), where EIFS is exterior insulation and finish system insulation type and MCM is metal composite material, and, cause of fire and level within the building at which the fire was thought to have begun (Figure 3.7, as reproduced from Hopkin et al. (2019)), where the maximum possible story where a fire could have started, halfway story height and first story are indicated by the dashed lines.

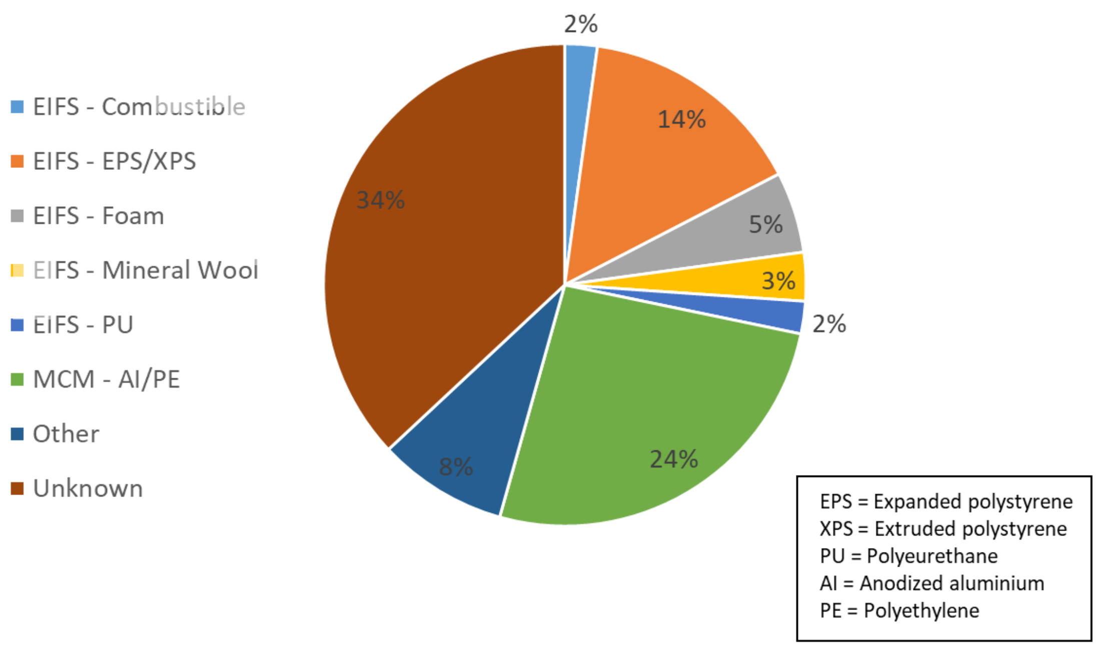


Figure 3.6 Façade Assembly Types, Broken Down by EIFS and MCM Panel Product (Spearpoint et al., 2019)

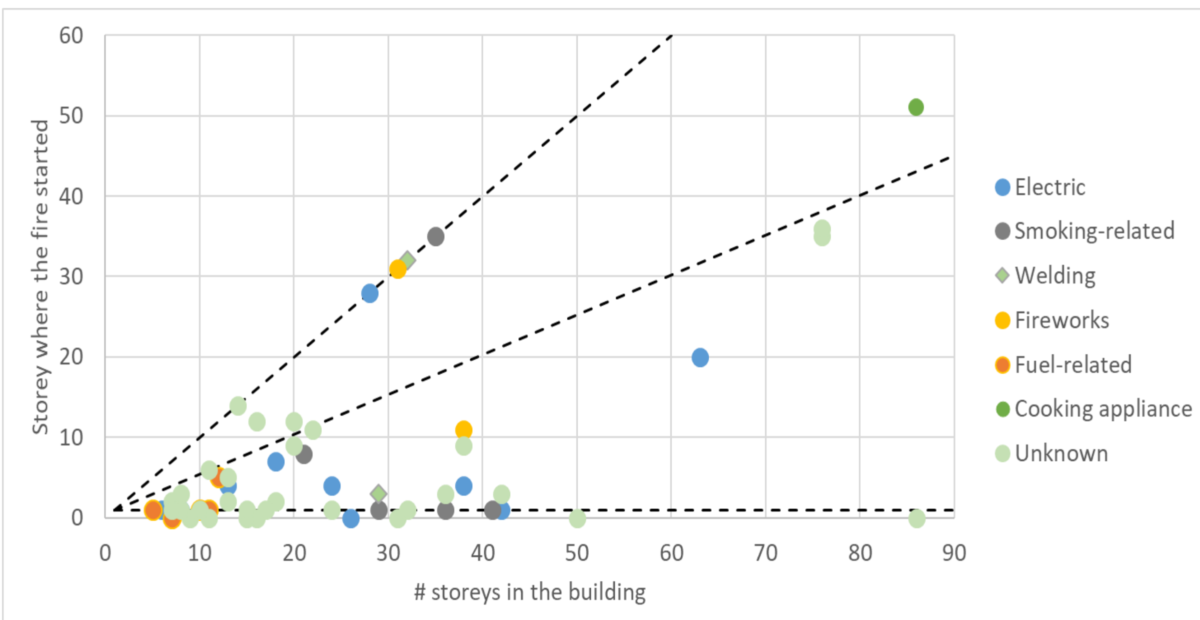


Figure 3.7 Cause of Fire, Story Level of Likely Fire Origin, Stories in the Building. (Spearpoint et al., 2019)

Reported findings include that 60% of the fatal fire incidents occurred in older buildings that had undergone some form of refurbishment; in incidents in which fatalities occurred, the buildings were less than 32 stories tall and had an EIFS-type assembly façade; and based on interpretation of very limited data, the reliability of sprinkler systems in façade fire incidents is around 80% (Spearpoint et al., 2019).

3.2 Representative Fire Incidents

In addition to data obtained from incident surveys, as reflected above, fire incidents involving 'green' or sustainable attributes of buildings can also be found in scientific studies (e.g., research reports, journal articles) and in the media or general literature. This section reflects a sample of fire incidents as identified in searches of these media. In some cases where data have been collected by others (e.g., reports, articles), the main report is listed, rather than the specific details of each event. This list should be considered exemplary more so than comprehensive. Some incidents noted below may also be captured in the above.

Table 3.11 Representative Fires Involving 'Green' Attributes of Buildings

Fire incident (Name and Year)	Description	Reference
Exterior Wall Systems		
Las Vegas (MGM Monte Carlo Hotel), USA, 2008	Object: Exterior wall systems Source: Welding on catwalk on the roof parapet 'Green' element (burned): Exterior wall and cladding systems	Beitel and Evans (2011)
Dubai (Tamweel Tower), 2012	Object: Exterior wall systems Source: Unstated – started on top floors 'Green' element (burned): Exterior wall and cladding systems	Shabandri and Agarib (2012)
Sharjah's Al Nahda area, Dubai (Al Tayer Tower), 2012	Object: Exterior wall systems Source: Unstated – started on ground floor 'Green' element (burned): Exterior wall and cladding systems	Kakande (2012)
Roubaix (Mermoz Tower), France, 2012	Object: Exterior wall systems Source: Balcony fire 'Green' element (burned): Exterior wall and cladding systems	Youde (2017)
Istanbul (Polat Tower), Turkey, 2012	Object: Exterior wall systems Source: Unstated 'Green' element (burned): Exterior wall and cladding systems	BBC (2012)
Chechnya (Grozny-City Towers), 2013	Object: Exterior wall systems Source: Reported as short cricuit 'Green' element (burned): Exterior wall and cladding systems	Taylor (2013)
Melbourne (Lacrosse Building), Australia, 2014	Object: Exterior wall systems Source: Balcony fire 'Green' element (burned): Exterior wall and cladding systems	Genco (2015)

Table 3.11 (cont.) Representative Fires Involving 'Green' Attributes of Buildings

Fire incident (Name and Year)	Description	Reference
Dubai (Address Downtown Hotel), UAE, 2015	Object: Exterior wall systems Source: Short-circuit in spotlight between 14th and 15th floor 'Green' element (burned): Exterior wall and cladding systems	Moukhallati (2016)
Dubai (Torch Tower), UAE, 2015/2017	Object: Exterior wall systems Source: unknown, start 50th floor 'Green' element (burned): Exterior wall and cladding systems	Greenberg (2015)
Baku, Azerbaijan, 2015	Object: Exterior wall systems Source: Unstated 'Green' element (burned): Exterior wall and cladding systems	Nazarli (2015)
Various	Object: Exterior wall systems Source: Various – report contains statistics and case studies of several events 'Green' element (burned): Exterior wall and cladding systems	White and Delichatsios (2014) Evans (2016) Spearpoint et al. (2019)
London, UK, 2017	Object: Grenfell Tower Source: Combined refridgerator/freezer unit on 4th floor 'Green' element (burned): Exterior wall and cladding systems	GOV.UK (2019) McKenna et al. (2019) Wieczorek (2017)
Worcester Park, Sutton (The Hamptons), England, 2019	Object: Exterior wall systems Source: Unstated 'Green' element (burned): Exterior wall and cladding systems	Jessel (2019)
Sharjah (Abbco Tower), UAE, 2020	Object: Exterior wall systems Source: Unstated 'Green' element (burned): Exterior wall and cladding systems	BBC (2020)

Figure 3.8 Grenfell Tower Fire (Source: Natalie Oxford, 2017.[1]

[1] This file is licensed under the Creative Commons Attribution 4.0 International license (https://creativecommons.org/licenses/by/4.0/deed.en). Photo downloaded from https://commons.wikimedia.org/wiki/File:Grenfell_Tower_fire.jpg (last accessed September 2020).

Table 3.11 (cont.) Representative Fires Involving 'Green' Attributes of Buildings

Fire incident (Name and Year)	Description	Reference
Energy Storage Systems		
Hawaii, USA, 2012	Object: Battery Storage System Source: Battery Storage System, 10-megawatt battery system, Kahuku wind farm 'Green' element (burned): Battery Storage System	Irfan (2015) Blum and Long Jr (2016)
Michigan, USA, 2012	Object: Battery System Source: General Motors Battery Laboratory 'Green' element (burned): Battery System	Hill et al. (2017)
USA, 2013	Object: EV Battery System Source: Cited – several Tesla vehicles 'Green' element (burned): EVs / EV Battery System	Bullis (2013)
Brisbane, Australia, 2018	Object: Solar Home Battery System Source: 'Green' element (burned): Battery System	Crockford (2018)
South Korea, 2018	Object: Battery Storage System Source: Battery Storage System 'Green' element (burned): Battery Storage System "At least 21 fires had already occurred at battery projects in South Korea, according to BloombergNEF" (Bloomberg) "in nearly every case the issue appears to have been poor management of batteries" (Energy Storage News)	Eckhouse and Chediak (2019) Colthorpe (2019)
Arizona, USA, 2019	Object: Battery Storage System Source: Battery Storage System 'Green' element (burned): Battery Storage System	Eckhouse and Chediak (2019) Blum and Long Jr (2016) McKinnon et al. (2020)
Electric Vehicle Battery Fires		
Various	Object: EV / EV Battery Source: B EV / EV Battery 'Green' element (burned): EV Battery Storage System	Sun et al. (2020b) Wikipedia (2020)

Table 3.11 (cont.) Representative Fires Involving 'Green' B Attributes of Buildings

Fire incident (Name and Year)	Description	Reference
Photovoltaic (PV) Systems		
Delanco, New Jersy, 2013	Object: PV System Source: Dietz and Watson Factory 'Green' element (burned): PV System and combustible insulation in roof system	Wills et al. (2014)
Florence Township, New Jersey, 2013	Object: PV System Source: Christmas Tree Shops Warehouse 'Green' element (burned): PV System	Wills et al. (2014)
LaFarge, Wisconsin, 2013	Object: PV System and wall of sustainable materials (old jeans) Source: Corporate headquarters of Organic Valley 'Green' element (burned): PV System and Wall System	Wills et al. (2014)
Webster Groves, St. Louis, MO, USA, 2013	Object: PV System Source: High School 'Green' element (burned): PV System	Shafer (2013b)
Boston, 2015	Object: PV System Source: 5-story Apartment Building 'Green' element (burned): PV System	Quiroga (2015)
San Francisco, 2015	Object: PV System Source: Home 'Green' element (electrical shock to FF): PV System	CBS (2015)

Figure 3.9 Aftermath of Delanco, NJ, Warehouse Fire (Courtesy of New Jersey State Fire Marshal Office)

Table 3.11 (cont.) Representative Fires Involving 'Green' Attributes of Buildings

Fire incident (Name and Year)	Description	Reference
Photovoltaic (PV) Systems		
Hartford County, MD, 2015	Object: PV System Source: Home 'Green' element (burned): House fire with PV System	Shafer (2015)
UK, various	Object: Photovoltaic (PV) Systems Source: Includes reporting of 81 PV fires involving various components and building / facility type 'Green' element (burned): PV system components and more (large database of incidents)	GOV.UK (2017)
Beavercreek, OH, 2019	Object: PV System Source: Walmart Retails Store 'Green' element (burned): PV System	WHIO (2019)
Louisville, Colorado, 2019	Object: PV System Source: Home 'Green' element (burned): PV System	Lopez (2019)
USA (2020)	Object: PV System Source: Various 'Green' element (burned): PV System	Sylvia (2020)
Fresno, CA, 2020	Object: PV System Source: Amazon Warehous 'Green' element (burned): PV System	Galaviz (2020)
Greenwich, CT, 2020	Object: PV System Source: House fire / solar panel 'Green' element (burned): PV System	Scofield (2020)
Timber Frame Buildings		
Nottingham, UK, 2014	Object: GlaxoSmithKline building Source: electrical fault in building under construction 'Green' element (burned): Wooden Frame	Williams (2014) Buckley (2015)
Boston, MA, USA, 2017	Object: Apartment building Source: identified as generator 'Green' element (burned): Wooden Frame	Rice (2017)
Waltham, MA, USA, 2017	Object: Apartment building Source: Unknown 'Green' element (burned): Wooden Frame	Knapschaefer (2017)
Solar Concentrator		
Bethlehem, PA, USA (2012)	Object: Cables Source: Radio station 'Green' element (ignition source): Solar concentrator	Panepinto (2019 (updated); 2012 (posted)) Shafer (2012a)

Figure 3.10 Fire in Timber Frame Apartment Building Under Construction (Source: Captain John Bonadio, Waltham Fire Department, as published at https://www.enr.com/articles/42484-what-local-officials-want-to-do-about-wood-frame-building-fires-in-massachusetts (last accessed September 2020), Courtesy of Waltham, Massachusetts Fire Department)

4. Scientific Studies

Information presented in this chapter is based on the findings of the literature survey whose methodology is described in Chapter 2. Emerging 'green' attributes have been selected through a combination of new trends and material identified through a combination of the literature study and input from the Project Technical Panel. The focus is on developments since 2012. Where possible review articles have been identified as a starting point for the interested reader to reach further into the existing literature, rather than presenting an in-depth presentation of the literature for each separate material, system or feature. In cases where information concerning fire performance was identified, this has been included and forms a basis for judgements of the "level of concern" presented in Chapter 6. In cases where the existing literature does not include information concerning fire performance, judgement is reserved for Chapter 6.

4.1 Emerging 'Green' Attributes and Trends

'Green' attributes are increasingly of interest to the building industry. In a recently report from Dodge Data & Analytics in collaboration with the World Green Building Council, on world 'green' building trends (Jones et al., 2018), indicated that the majority of new construction expects to be 'green' by 2021 although only a small number of these buildings will actively seek certification. The most high-level 'green' projects are, however, consistently seeking recognition through certification. Indeed, the majority of 'green' building are not in this segment, i.e. certified, and the gap between the certified and non-certified projects appears to be growing.

The major drivers globally to using 'green' attributes in buildings are (in order of priority) client demands, environmental regulations and an aspiration to create healthier buildings, although the relative importance of these drivers varies from country to country. The highest barriers to increasing 'green' building activity appears to be higher (perceived or actual) initial investment costs and lack of political support or incentives, although lack of training and an inability to prove the business case for 'green' buildings through lowering life-time costs were cited in just over 20% of responses. There is a risk that perceptions of 'green' building certification being reserved for the most high-profile cases may be further slow the broad acceptance of such certification schemes.

In the World Green Building Trends report, there is a dedicated section on Green Technology and trends. Key outcomes relate to energy performance meaning that insulation will continue to be an important issue in 'green' building design. As this specific issue has been identified as challenging from a safety point of view it will be discussed in more detail in the next section. Other key trends are largely related to implementation of building information models (BIM) and how these can help building designers and owners to make 'green' choices all through the design process and whole building life cycle, e.g. material choices, system choices, floorplan choices and their impact on the overall carbon footprint of the building. While BIM are being developed to include calculations of carbon footprints these do not presently include fire safety considerations and have not yet been broadly adopted. Further, the proper use of data created by sensors in 'green' buildings can provide information that can be used to improve energy efficiency and occupant engagement but could also potentially be used to promote safety.

Some specific new technologies that are of interest in the context of 'green' buildings include, but are not limited to:

- *Building-integrated Carbon Capture.* Carbon capture and storage (CCS) has been a field of research since the 1970s (Marchetti, 1977), typically with a focus on CO_2 capture from industrial applications and storage in suitable geological formations (Arshad et al., 2019). While this has met mixed reception, the applications and their impact are limited. Recently, Bryan and Ben Salamah (2018) described a novel application of carbon capture and recovery technology through the integration of Moisture Swing Air Capture Technology into building shades to allowed the widespread implementation of carbon capture and recovery into a functioning building element on a building façade. The implementation into a building's façade is inspired by widespread building-integrated photovoltaic systems. Given the density of suitable buildings in many urban areas, the technology could potentially provide a complement to other initiatives to reduce carbon emissions from 'green' buildings should they meet widespread adoption. The systems are, however, presently only available at an early prototype stage.

- *Additive Manufacturing/3D Printing.* Additive manufacturing (also commonly called 3D printing) has been developed since the 1980s (Matias and Rao, 2014; Kamble et al., 2018). Early applications of 3D printing have focused on the production of components to allow the relatively low investment development of early prototype materials without the need for expensive investments in traditional industrial machines or tools. More recently, the technology has been applied to building applications where it is hoped that similar savings may be made in manufacturing costs (Delgado Camacho et al., 2018) or in building construction sustainability by reducing waste and material production emissions (Williams, 2019) and life-safety at construction sites (Tay et al., 2017). While many different types of 3D technologies exist, building construction applications have focused on cementitious building elements as bespoke construction elements or prototypes. The use of 3D printing in such applications has the potential to remove the 35-60% of the construction cost associated with *in situ* casting and formwork (Pshtiwan et al., 2019). The application of 3D printing in the construction industry is not, however, limited to cementitious materials and can include both polymer printing (including bioplastics) and metal printing or composited of different materials (Delgado Camacho et al., 2018; Williams, 2019).

- *Low carbon emission concrete.* Concrete has enjoyed broad application in the construction industry since its first applications in ancient times (Sargent, 2019). There are, however, significant concerns with the carbon footprint of production of traditional concrete mixtures (Kim et al., 2013). Recent work indicate that low-carbon emission concrete production in support of sustainable construction is possible using a number of different methods (Wu and Feng, 2014; Brownell, 2019; Shi et al., 2019; Skanska, 2019). It should be noted that concrete can represent some fire safety challenges, in particular when it is very low porosity (such as ultra-high performance concrete) (CEN, 2004; Jansson, 2013). An additional change which is attracting some attention is the use of carbon-reinforced polymers as rebars instead of traditional steel. This has the potential to reduce the carbon footprint of the concrete and to reduce the risk of corrosion of the rebars where especially corrosive conditions are expected (e.g. in bridges) (Carvelli et al., 2013). Little work is available concerning the fire performance of such rebars, however, and more work is needed to investigate the fire spalling properties of such concrete structures given concern about the fire performance of rebars that are themselves combustible (Hamad et al., 2017).

- *Hempcrete.* The inclusion of natural materials in concrete can be employed as a way to reduce the overall embodied carbon in concrete. Hemp concrete or hempcrete has been employed increasingly as a 'green' building material in the past 1-2 decades (Bevan and Woollley, 2008). Similar to traditional structures, such as wattle and daub, it can be used to moderate the indoor temperature due to its hygrothermal responsiveness (Piot et al., 2017). It is a lightweight material which, as with traditional concrete, requires some reinforcement to be used as load-bearing, has a low CO_2-footprint and can be made from wholly renewable material (Gołębiewski, 2017).

- *Alusion panels.* Stabilised Aluminium Foam, or Alusion™, represent a new material technology that can be used in a number of construction applications including as aesthetic façade finishes, interior walls, acoustic panels on ceilings, displays, signage and lighting (Williams, 2019; Cymat Technologies Ltd, NA). The material is reported to be wholly recyclable.

- *Inflated Steel Structures.* Interesting architectural design was developed by Oskar Zieta as part of his PhD with an initial focus on furniture applications and interior design (Dumiak, 2009; Splash, 2012). In recent applications the technology has been applied to the production of at least one aesthetically pleasing light-weight steel structure using organic shapes (Syed, 2017; Brownell, 2019).

- *PET for Buildings*. Material recycling is a strong societal trend. Sustainable or 'green' buildings often rely on the use of recycled material in the building and furniture and fixtures in the interior design. Polyethylene terephthalate (PET), is the most recycled polymer today at a rate of just over 20 percent (Brownell, 2019). Political initiatives such as the Green Deal for Europe (Commission, 2019) or the Green New Deal in the US (Friedman, 2019) promote the use of recycled material amongst many other initiatives. It is important to keep in mind the combustibility of plastics material (whether recycled or not) and their fire performance in the specific application to ensure that safety is maintained while sustainability is improved.

- *Interactive printed graphene*. Digitalisation is becoming increasingly entrenched in our society with the introduction of many novel and interesting applications to the built environment. Recently Kemp (2017) presented interactive printed graphene as one of 11 materials that can shape our future. Graphene has a myriad of interesting properties that make it an attractive material for building applications, e.g. it is high strength, versatile and conducts electricity. Printing circuits directly onto paper or facades can create interactive applications in the future. There are, however, clear fire safety implications given that carbon is accessible to oxidation at high temperatures through combustion. The technology has many promising applications as exemplified by the recently started Graphene Engineering Innovation Centre at Manchester University (Georghiou, 2018).

- *Novel biological material*. A variety of novel biological material have been identified as potential game changers for material production with future applications outside of their typical domain of the medical industry into the more traditional building industry (Kemp, 2017; Brownell, 2019). Self-organising biological material might offer opportunities for self-repairing materials (Freeman et al., 2018) while new research into biofaçades could pave the way to additional carbon capture technology using algae or microbial cellulose (Poletto and Pasquero, na). Similarly, the use of mycelium-based substrates to grow rather than manufacture building materials is being explored (Elsacker et al., 2019). Applications are still largely on the drawing board and have not achieved broad acceptance to date.

- *BIM and digitalisation*. Building information models (BIM) are increasingly gaining traction as tools to improve communication of information during the design and building phase of construction. There is a need to improve the transfer of BIM to the operation and maintenance phase of the project (Sadeghi et al., 2019). At the same time digitalisation of buildings is increasing and is a fundamental part of 'green' building design (Dryjanski et al., 2020). Many buildings (even those that are not typically seen as 'smart') contain significant technology to control building climate and other activities (such as security), but transitioning from a traditional building to a smart building when the building has not been designed as such is fraught with difficulties (Barker, 2020). The use of BIM as a method to leverage digitalised features in buildings to make them smart is a powerful tool (Tang et al., 2019). The implementation of this technology is still nascent and typically isolated to high-end buildings but could represent significant potential to migrate traditional buildings into sustainable constructions, e.g. in conjunction with renovations.

- *Phase changing material*. The use of phase change materials (PCM) in building enclosures offers some advantages for maintaining indoor comfort and reduce overall energy consumption in buildings (Liu et al., 2018). PCMs can be divided based on their chemical composition (organic, inorganic or composite) or their phase range (solid-solid, solid-liquid and liquid-gas) (Cui et al., 2015). PCM building material has mainly been developed for wall applications (Zhu et al., 2018). Despite the high level of interest, there are still unresolved questions, including the level of fire safety due to the potential for toxic emissions during a fire from some PCMs and the flammability of certain PCMs (Kalnæs and Jelle, 2015).

- *Passive House*. While not new, there is an increased emphasis on homes and other buildings that use very little energy. The passive design strategy for buildings models and balances a comprehensive set of factors, including heat emissions from appliances and occupants, to keep a building at comfortable and consistent indoor temperatures throughout the heating and cooling seasons. It is based on a set of five design principles (PHIUS, 2020): the building envelope is extremely airtight, preventing infiltration of outside air and loss of conditioned air; employs high-performance windows (double or triple-paned windows depending on climate and building type) and doors; uses some form of balanced heat- and moisture-recovery ventilation; and, uses a minimal space conditioning system. The foundational design principles of greater insulation, airtight building envelopes, high-performance windows, energy recovery ventilation and managing solar gain originated in the United States and Canada in the 1970s, but were advanced in Europe and gained broad attention with the formation of the Passivhaus Institut (Passive House Institute) in Germany in 1996 (PHI, 2020). From a fire safety perspective, the main issues of potential concern are the possible use of combustible insulation, overpressures and unsafe conditions that can result during a fire, including high CO, low O_2 and limited time for escape (Molkens, 2011; Debrouwere, 2012; Fourneau et al., 2012; Hostikka et al., 2017; Janardhan and Hostikka, 2017) and the lack of mechanical ventilation, which if present may have some benefit for smoke control (particularly in larger buildings).

4.2 Exterior Materials and Systems

Façade and Wall Systems

Following the tragedy of the Grenfell Tower fire in London in June 2017, there has been significant global focus on fire performance of exterior wall and façade systems (e.g., see for example van Hees et al. (2020)). However, concerns with such systems were identified previously (Tidwell and Murphy, 2010; Meacham et al., 2012), and a comprehensive study on this topic was undertaken by the FPRF in 2013 (White and Delichatsios, 2014). Indeed, numerous fires in façade and external wall systems have been catalogued since the late 1900's (see the previous chapter for a selection of such fires).

Research and recent fires have shown that fires involving the exterior of a building should not be neglected (see for example Wade and Clampett (2000), Alpert and Davis (2002), Peng et al. (2013) and van Hees et al. (2020)). When considering façades and curtain wall systems, different types of hazards/risks should be considered (Smolka et al., 2013; Smolka et al., 2016; van Hees, 2016). New and innovative complex systems introduced in new high-rise buildings, such as the External Thermal Insulation Composite Systems (ECTIS) have been developed in part due to demands on better thermal insulation in sustainable buildings (Potrč et al., 2016). German industrial enterprises have, however, experienced problems in finding insurance coverage (Kotthoff and Riemesch-Speer, 2013) due to an unwillingness to assume the risk due to combustible building insulation in some systems.

Fire performance testing of façade systems has been conducted since the 1990's and a flora of test methods have developed globally (Martinsson, 2018). As recently as 2016, the EU issued a tender asking for consortia to develop a pan-European approach to façade testing. The tender was awarded to a Consortium of five test labs across Europe under the leadership of RISE Research Institutes of Sweden. The final report from their work has recommended two test methods and a variety of performance criteria (Boström et al., 2018). Additionally, test methods are available in Canada (ULC, 2013) and the US (Nam and Bill Jr, 2009; Agarwal, 2017; ANSI/FM Approvals, 2017a; ANSI/FM Approvals, 2017b; NFPA, 2017; NFPA, 2019c; Agarwal et al., 2020) or globally through the International Standardisations Organisation (ISO, 2002b; ISO, 2002a). While a variety of test methods are available, they reflect a wide spectrum of scenarios, including exterior fires, interior flashover fires, and fires originating within cavity. Different tests also reflect a range of severity, depending in part on the strength of the initiation fire, and amount and arrangement of fuel involved in the test (Jamison and Boardman, 2016).

One challenge concerning the fire safety of façade systems is their complexity which can lead to difficulty in testing all possible product combinations and opens for incorrect installation. Indeed, several of the high-profile fires presented in the previous chapter have been blamed on incorrect installation of otherwise code compliant products; or the use of non-code compliant variations of an otherwise code compliant façade system due to lack of understanding of the implications of seemingly small changes on the overall fire performance of the system. Further, the tests that are available have the additional challenge that they typically cover limited and specific cases and general application of them can be problematic. In this context, the development of relevant acceptance criteria is also a challenge due to the complexity of many façade systems.

Given the daunting task of implementing full scale testing of all possible façade products, modelling could be seen as a potential tool to assess extended applications for a small range of tested products using performance-based approaches. While this approach is often used as a complement to testing, much work is still needed for its full implementation in relation to façade systems. Most advanced models today have been created for simpler solid materials (Janssens et al., 2003). More research is needed to extend the application of performance based fire safety engineering for these complex systems (Didieux, 2013; Mikkola et al., 2013). Until more robust and reliable computational modelling is available, based on quality small-scale test data of material performance, large-scale tests remain important to understand the fire performance of complex façade systems. Ultimately such large-scale testing provide can also provide the needed validation for numerical modelling which is currently lacking.

There are also some concerns with wall system design for smaller buildings, such as one- and two-family domestic housing. In particular, it has been noted that the use of double-thick wall and roof systems, to facilitate added layers of insulation, may impact firefighting operations, since the firefighters may not expect a roof of twice the thickness if they are trying to cut in a vent for smoke and hot gases (Meacham et al., 2014; Shafer, 2014). Buildings with this 'superinsulation' approach may also be prone to overpressure situations (see discussion under Passive House). Another wall system that is used on some locations is the Trombe wall (Shafer, 2012b), a typically south-facing masonry wall with a dark, heat-absorbing material on the exterior surface, spaced a short distance from a single or double layer of glass. This arrangement allows heat to be absorbed by the dark surface, stored in the masonry wall, and conducted slowly inward. The potential issue for firefighters is that it looks like a darkened window, but it is not an operable window, and does not afford direct access to the home.

Timber Facades

The use of timber in high-rise buildings is becoming increasingly popular as a means to improve the overall sustainability of the building (Yamanashi, 2015; Pomponi and D'Amico, 2017; Arkar et al., 2018), but the use of wood in façade systems is challenging from a fire safety perspective (Boström et al., 2016; Boström et al., 2018). Indeed, recent testing with three façade systems (one inert, one plywood without ventilation and one plywood with a ventilation cavity behind) indicated that the wooden façade could conceivably result in significantly higher heat release rates and flame spread (Boström et al., 2016). Models have been developed to assess the fire resistance of timber façades and other timber features in buildings (Östman et al., 2017). There are still, however, technical challenges associated with the use of timber in high rise buildings in general (see for example Law and Hadden (2020)), and the need to consider the fire performance of timber buildings features including façade systems (Loebus et al., 2013; Garay Martinez et al., 2017), connections (Dagenais, 2016; Nicklisch et al., 2019), both structural and non-structural members (Ramage et al., 2017).

Timber façades are not a single type of structure. When conducting a scan of existing literature, numerous applications of timber to the building envelope were found. In some cases a simple timber based prefabricated structure was investigated (Loebus et al., 2013; Gasparri and Aitchison, 2019) while in other cases more complex composite structures were evaluated, e.g. glass-timber structures (Schleicher, 2016), multi-layered phase-changing material (Arkar et al., 2018), metal-timber composite solutions (Nicklisch et al., 2019), and double-skin timber facades (Pomponi and D'Amico, 2017). The number of design applications of timber to building façades is limited only by the imagination of the designer and the fire performance regulations. Indeed, Hildebrandt et al. (2017) noted policy impacts on the full adoption of timber structures (independent of whether they are structural or not) as divided into "stick" (meaning regulations), "carrot" (meaning market subsidies) and "sermons" (meaning information to promote the acceptance of new timber applications). Depending on the success of these various instruments, timber construction has been adopted to varying degrees globally. Indeed, in the façade system debate that has flourished since the occurrence of the Grenfell fire in the UK (Moore-Bick, 2019), combustible façade systems have all come into question which may hamper the broad adoption of timber façades.

Due to the flexibility of timber in construction, no single assessment of risk of 'timber façade' is possible and the reader is urged at the outset of any risk assessment to take careful consideration of whether the timber features are load-bearing or not, whether they are exposed or not, as this will impact on their commiserate fire risk.

Organic Insulation types

As the building sector moves towards more energy-efficient buildings we are seeing a clear increase in the use of insulation materials (Papadopoulos, 2005). The shelf-life of a typical external thermal insulation composite system (ECTIS) is approximately 25-30 years, even with proper maintenance and care. When removing many insulation materials there is little or no chance of material recycling with traditional systems (Tůmová et al., 2017). Therefore the sustainable building industry has increasingly turned their interest towards natural, potentially biodegradable, insulation materials. Different types of material have been considered, including but not limited to, cork, straw, flax, hemp, sawdust, corn husks, sheep's wool and other natural products and by-products (see e.g. Papadopoulos (2005), Palumbo Fernández (2015), Krenn et al. (2017)). A review by Asdrubali et al. (2015) proposed a division of unconventional materials into two categories based on whether they are natural (e.g. reeds, bagasse cattail, corn cob, cotton, date palm, durian, oil palm fiber, pineapple leaves, rice, sansevieria fiber, sunflower and straw) or recycled (e.g. glass foam, plastics, textile fibers and others).

Many of these materials have significant advantages in terms of being low-cost, resolving potential problems concerning disposal of waste streams by repurposing these materials to useful applications; but, they also pose serious challenges in terms of poor or varied material quality, anisotropic performance and flammability. Some efforts have been made in recent years to address these challenges (Asdrubali et al., 2015; Palumbo Fernández, 2015) but there is still some distance before we would expect to see broad application of many possible solutions.

Non-traditional Window Framing Members

A variety of materials are being used or under investigation as alternatives for traditional wooden frames for windows. Energy performance is typically a driver of 'green' assessment in buildings and windows are responsible for a large loss of energy from the building which in turn is impacted by both the window itself and the choice of frame material. The choice of frame material has a significant impact on the overall environmental impact of the window construction but also in terms of the thermal losses through the window and its frame and connection to the façade (Sinha and Kutnar, 2012; Vinnichenko et al., 2018).

Materials that are increasingly under consideration include: different types of composite material (e.g. combinations of natural material and plastics (Rahman et al., 2008), or enhanced thermal performance with aerogels to reduce heat losses (Paulos and Berardi, 2020)); and various plastic material (e.g. PVC (Vinnichenko et al., 2018)). The materials pose advantages from a manufacturing point of view and in some cases may be particularly cost effective but no single solution fits all applications and in some cases the holistic life-cycle benefits may be greater for traditional approaches (Sinha and Kutnar, 2012).

An experimental investigation of different wooden and plastic or composite framed windows conducted as part of a larger study by UL (Kerber, 2010) indicated differences in the time to failure for different window structures but this was most clearly related to the use of single or double glazing in the windows and whether the window frame allowed for expansion of the glass pane during heating rather than to the framing material chosen. It remains unclear whether non-traditional window framing members represent a significant increase in fire risk.

Green Walls and Roofs

Interest in green wall and roof systems has increased since the 2012 report (Meacham et al., 2012). While both green roofs and walls have a relatively long history of simple implementation, a number of new product systems has been increasing in recent years (GOV.UK, 2013). Indeed, recently there have been some high-profile examples of implementation of green walls, e.g. Once Central Park in Sydney (Nouvel and Beissel, 2014) and Plug-in City 75 in Paris (Singhal, 2017). Such buildings are being built new or created from existing building stock in need of renovation, in response to buyer's interest in signature architecture for use in our evolving view of what makes up a modern city. More such buildings should be expected in the future. There is also an increase in the use of blue roofs, which are focused on water attenuation (NFRC, Undated).

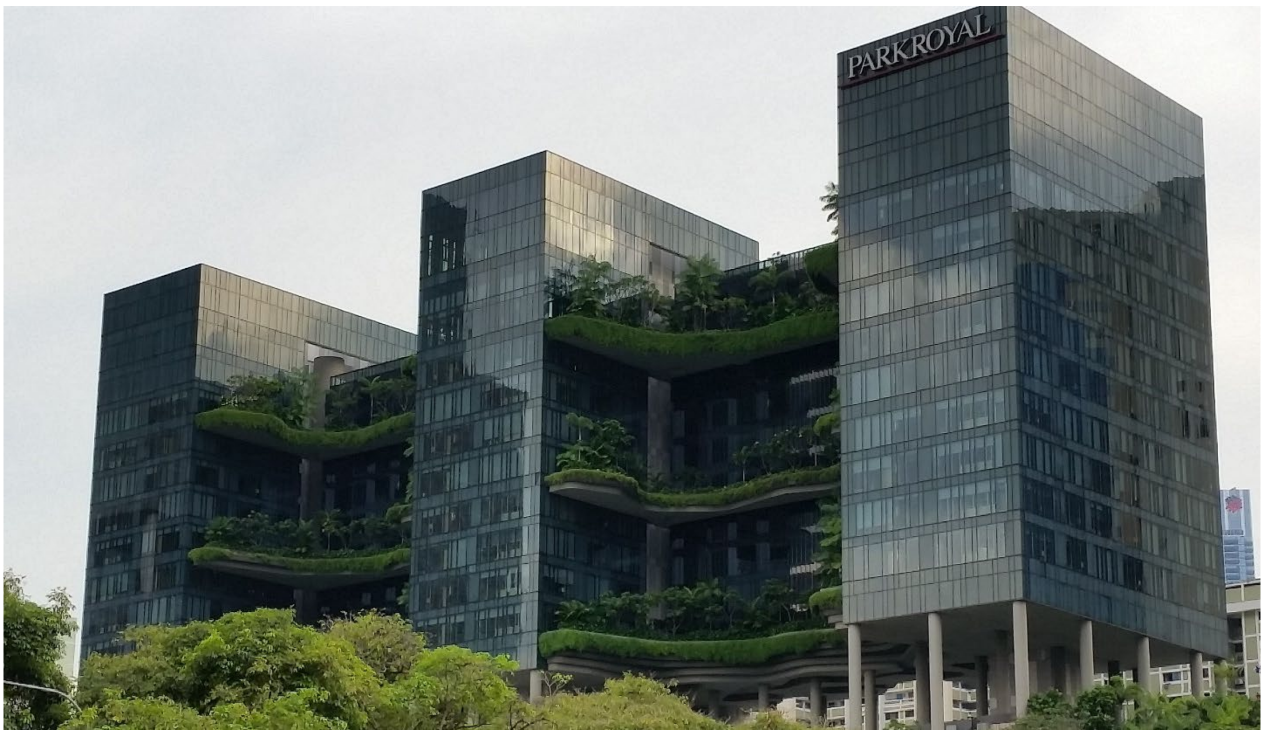


Figure 4.1 Building with Green Balcony Feature (Source: Brian Meacham)

In the UK, a review was conducted by the UK Government's Department of Communities and Local Government (GOV.UK, 2013) of guidance documents available at the time on fire performance of green roofs and wall systems, to illustrate the results of testing which has been carried out on such systems, and to provide guidance on the fire performance aspects of green roof and wall construction and maintenance. According to the UK report it is useful to divide green roof systems into three types based on the number and thickness of layers of the system, i.e.:

1. Extensive. Lightweight, low maintenance (traditional) green roof which typically has low ground cover based on mosses, herbaceous plants and succulents. The typical depth is 80-150 mm and the organic content is typically <20%.
2. Semi-intensive. This is an intermediate type of green roof system, with a substrate depth of 100-200 mm which allows somewhat greater plant density and size and typically requires a permanent irrigation system.
3. Intensive. These systems are typically referred to as 'roof gardens', with a substrate depth >200 mm which can accommodate any type of vegetation depending on the needs of the plants for substrate

depth and the design of the building. Such systems typically require permanent irrigation systems and complex maintenance systems.

Green wall systems are often referred to as 'living walls'. Green walls are also typically divided into three types of systems:

1. Climbing plants. In their most basic form, a green wall can be comprised of climbing plants encouraged to grow on a façade, either with or without a dedicated trellis system.
2. Hydroponic green walls. Plants are planted in plastic mesh, geotextiles, fabrics or horticultural mineral wool or combinations of these in supporting frames. In hydroponic systems the plants require no substrate and obtain all nutrients through irrigation water.
3. Modular green walls. These are typically planting modules which are fixed to a wall or frame, combined in such a way to create growing wall sections.

There are many aesthetic and environmental benefits of green roof and/or wall systems, but there has been some concern about whether they might constitute an increased fire hazard. A number of studies have considered this and the consensus appears to be that provided the plant-based systems are kept moist they should be relatively ignition resistant (GOV.UK, 2013; Elias et al., 2017). However, given the organic nature of the material and the fact that its fire performance will depend on external factors, such as maintenance and weather conditions, there is a need for further research to establish suitable fire protection methods before their widespread implementation.

Ultra-High Performance Concrete (UHPC)

Increasingly, research has investigated the potential to leverage the very high strength of ultra-high performance concrete (UHPC) to reduce the material use in building elements (Barbos et al., 2014; Kromoser et al., 2019) and thereby improve its sustainability. UHPC exhibits improved strength, durability and long-term stability relative to traditional concrete formulas. According to Graybeal (2006), the compressive strength of UHPC is greater than 150 MPa, internal fibre reinforcement is used to ensure non-brittle behaviour, and there is typically a high binder content with special aggregates. Further, UHPC tends to have a very low water content, requiring optimized granular packing and the addition of high-range water reducing admixtures to achieve sufficient rheological properties for use. Significant fire safety challenges remain given the tendency for beams and girders with narrow cross-sections to spall under fire exposure. More information is provided in a similar section under the section below on *Structural materials and systems*, although some information is repeated to make the sections individually reasonably complete.

Double Skin Façades

Double skin façades, not to be confused with 'double glazing' which is typically used to signify traditional framed windows with two window panes, has increasingly been employed in high-rise buildings as their use offers numerous architectural advantages both in terms of lighting, energy efficiency and aesthetics (Wang et al., 2017). Unfortunately, glazed façades offer some fire safety challenges, in particular in double glazed curtain walls where the space between the layers of glazing can facilitate fire propagation unless proper attention is placed on fire partitioning within the façade structure (Chow et al., 2015; Jönsson et al., 2016).

To explore smoke movement within double-skinned façade under different conditions, Ni et al. (2012) conducted a series of experiments in which temperatures required to break glass were obtained, and then temperature rise between double-skinned façade was investigated. In this work, temperatures were insufficient within the cavity to break glazing in upper levels. Maisto and Gollner conducted saltwater modelling and FDS modelling on a representative double-skin façade geometries with louvers to assess similar issues, with scenarios including louvers and four different angles and no louvers at all (Meacham et al., 2017). While glass breakage temperatures were not assessed, outcomes suggest the potential for high velocities and temperatures under certain conditions, which could lead to interior façade breakage and smoke or flame re-entry. Thomas et al.

(2018) also noted that fire or smoke spread potential was a concern, but through CFD modelling concluded that provided the vents to the double-skin facade close in a fire, and flashover does not occur in rooms adjoining the DSF, or sprinklers are installed, smoke spread to higher floors via the double-skinned façade is limited.

4.3 Façade Features

Out-of-Plane Geometry

Passive systems to reduce the heat concentration in tall buildings often require the design of out of plane façade geometries (Stevanović, 2013). Such systems can improve indoor comfort and reduce heating, cooling and lighting energy consumption in buildings. A variety of in-plane and out-of-plane solutions can be used such as optimizing window-to-wall ratios and the associated horizontal overhang or the depth and inclination of windows, the building aspect ratio, window orientation, louver use and angles and the use of novel façade design. Designs can be both aesthetically pleasing design features and functional aspects of the building design itself, improving the overall energy consumption requirements.

Standard fire tests for façades are essentially designed with flat surfaces or balcony structures in mind and bespoke methods may be needed to deal with novel structures. Some previous work has indicated that the existence of horizontal projections or spandrels between window features may increase fire performance of façades by reducing the heat flux on the façade by forcing the fire to move away from the façade (Oleszkiewicz, 1991), so some structural modifications based on design considerations may be beneficial for fire performance.

Solar Radiance Concentration

Reflection of light from high-rise façades is a commonplace occurrence in modern cities, in particular with the use of large glass façade systems to improve energy efficiency in buildings. What can be seen as little more than a nuisance, does have the potential to create more dire risks due to the confluence of highly reflective material and non-linear façade designs (Danks et al., 2016b). Examples include the Disney Concert Hall in LA which has a highly reflective metal façade which ultimately needed to be partially roughened to reduce reflection (Schiler and Kensek, 2009), the Vdara Hotel and Spa in Los Angeles where the glass façade made the pool area too hot for guest to comfortably be able to use (MSNBC.com, 2010), and the Shard in London where the Southeaster Rail Company issued warnings to its train drivers to slow down due to excessive glare from the building (CityA.M., 2012), just to name a few.

A recent review article and book chapter have both cited the need for universally accepted limits for reflected sunlight and better practice in designing buildings in the future (Danks et al., 2016a; Wen et al., 2020).

4.4 Alternate Energy Sources

Photovoltaic Panel Systems

Fire hazards of photovoltaic (PV) systems were noted in the 2012 report (Meacham et al., 2012). Since then, numerous research efforts have been undertaken by such groups as Underwriters Laboratories, Inc. (UL) (Backstrom et al., 2009; 2010; 2012c; 2012a; 2012b; 2012d; 2013; 2013; 2014), the Fire Protection Research Foundation (Wills et al., 2014; Sipe, 2016) in the US, the Building Research Establishment (BRE) in the UK (GOV.UK, 2017; Pester et al., 2017; Coonick and Bregulla, 2018), and the International Energy Agency (IEA) (Namikawa et al., 2017; Sinha et al., 2018).

Observing the concerns that had begun to be raised around 2009 by the fire service and others due to fire and PV systems, the Solar America Board for Codes and Standards (Solar ABCS) developed a research program to investigate whether and how the presence of stand-off mounted PV arrays may affect the fire class rating of common roof covering materials (Sherwood et al., 2013). A series of tests were conducted by Underwriters

Laboratories, Inc. in Northbrook, IL, with assistance from representatives of Solar ABCS (Backstrom et al., 2009; 2010; 2012c; 2012a; 2012b; 2012d; 2013; 2013; 2014). This testing helped facilitate a new resistance to fire test for solar panels and changes to the 2012 International Building Code and 2012 International Residential Code (SolarABCS, 2011) and beyond.

In 2014, the Fire Protection Research Foundation (FPRF) facilitated an 'all hazards' literature review to compile information on a wide variety of hazards and damage potential created by the installation of photovoltaic (PV) systems on commercial roof structures (Wills et al., 2014). In this report, a number of major PV fires in 2013 alone were identified, along with advances and gaps in testing and certification of PV systems. A follow-up study focused on roof assemblies conducted an overview of test methods and suggested necessary testing to investigate the efficacy of mitigation strategies (Sipe, 2016). Investigation of the use of arc-fault circuit interrupters has also been presented (Armijo et al., 2016).

Additionally, the International Energy Agency has produced reports concerning health safety concerns with emissions from PV panels in a fire (Sinha et al., 2018) and best practices for PV and firefighter operations from a selection of countries around the world (Namikawa et al., 2017). There is some indication that the space between the roof and the installation can create flue-like conditions accelerating the spread of flame. In this case the size of the space and angle of incline are important parameters to identify the fire risk. Some research has recently been conducted to address this question (Kristensen et al., 2018; Kristensen et al., 2020).

Energy Storage Systems

Since 2012 there has been an increase in the use of lithium ion (Li-ion) batteries in energy storage systems (ESS) across a broad spectrum of suburban and urban areas, as components of electrical utilities as well as single family dwellings and commercial buildings, from low- to high-rise. In 2014, the US Department of Energy developed a strategic plan for ESS safety (US DOE, 2014). The goal of the plan was to develop a high-level roadmap to enable the safe deployment energy storage by identifying the current state and desired future state of energy storage safety focused along three streams: Science-based Safety Validation Techniques; Incident Preparedness; and, Safety Documentation. Activities arising from this plan included review of ESS codes, standards and regulations relevant to incident response (Conover, 2014). Work in these areas continues under the Energy Systems Safety Collaborative (Sandia, 2020).

In 2015, the FPRF launched a project to develop a hazard assessment of the usage of lithium ion batteries and to facilitate the development of safe installation requirements and appropriate emergency response tactics (Blum and Long Jr, 2016). The report found that there is a lack of testing concerning fire performance of Li-ion ESS, and that code recommendations (e.g. from IFC, NEC and NFPA codes) are patchy and at times conflicting. Information concerning actual fires in ESS is largely anecdotal as there is no fire statistical code associated with such installations, making it difficult to obtain an overview of the potential fire safety problems associated with such installations.

Similarly, a study of considerations for ESS fire safety was conducted by Det Norske Veritas (USA) on behalf of the New York State Energy Research and Development Authority (NYSERDA) (Hill et al., 2017). The main conclusions of the study were that the installation of ESS in buildings increases risk although these were seen to be manageable within existing building codes with established firefighting methods. It was noted, however, that the question of the emission of exotic toxic species needs to be addressed as part of the risk evaluation.

Building Integrated Photovoltaics (BIPV)

Building integrated photovoltaics (BIPV) have the potential to revolutionise the use of PV systems in urban environments (Moraitis et al., 2018). The International Energy Agency has produced reports concerning health safety concerns with emissions from PV panels in a fire (Sinha et al., 2018) and best practices for PV and firefighter operations from a selection of countries around the world (Namikawa et al., 2017). Further the IEA has issued an analysis of requirements for building integrated photovoltaic panels (Berger et al., 2019).

The definition of a BIPV is somewhat fluid and PV systems discussed previously within this section could at times be defined as BIPV, e.g. certain roof or wall PV systems. The main defining feature of BIPV is that it is a construction element within the building, i.e. if the BIPV module were to be dismounted, it would have to be replaced by an appropriate by an appropriate construction product (Berger et al., 2018). The BIPV differs from building attached photovoltaic systems (BAPV), which are photovoltaic systems that are attached to the building envelope and do not comprise part of the building structure (Berger et al., 2018).

An example of a BIPV product, which also is an exterior wall system, is EnergyGlass™, a transparent laminated glass system which can be simply integrated into most building window designs, that continually collects and creates electricity from sunlight, diffused light and artificial light. The direct current electricity that is produced can be inverted and returned to the grid, used to charge batteries, and/or be wired direct to electronics (EnergyGlass, Undated).

A compilation of user needs for BIPV (Boddaert et al., 2019), identified the following fire safety considerations:

a) the load-bearing capacity of the construction should be assumed for a specific period of fire exposure;
b) the generation and spread of fire and smoke within the construction works should be limited;
c) the spread of fire to neighbouring construction works should be limited;
d) occupants must be able leave the construction works or be rescued by other means;
e) the safety of rescue teams should be taken into consideration.

Also, as with any PVS, ignition potential and shock hazard potential should be considered.

An example of a BIPV application is illustrated in Figures 4.2 and 4.3. This specific system was designed into the FKI Tower in Seoul, Republic of Korea, by the firm Adrian Smith + Gordon Gill Architects. which served as the Design Architects and Design Firm for the project. Figure 4.2 illustrates the components of the system. Figure 4.3 is a photograph of the exterior system as constructed in the FKI Tower.

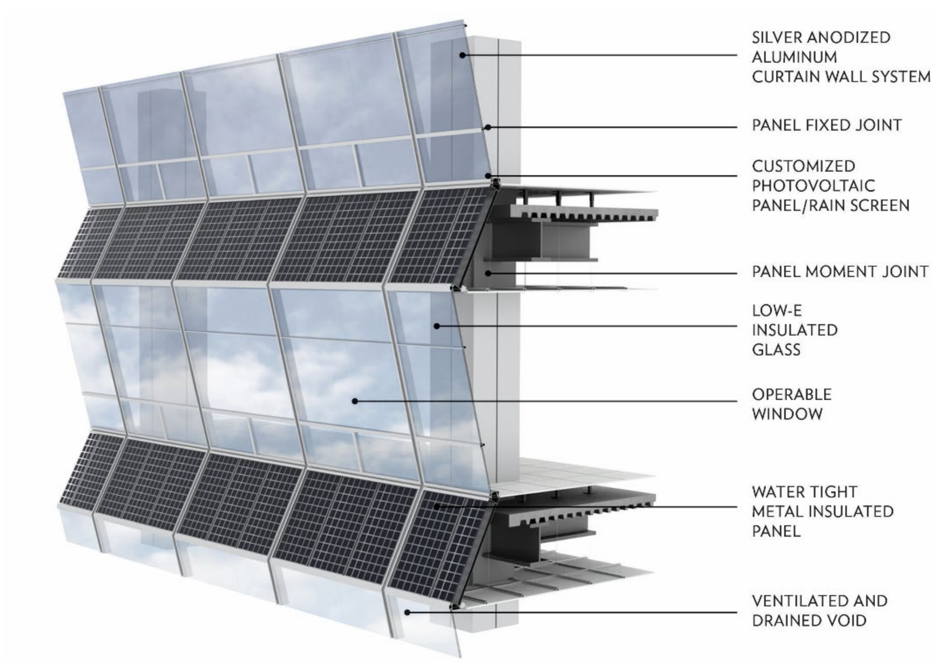


Figure 4.2 FKI Tower Exterior Wall Diagram (©Adrian Smith + Gordon Gill Architecture, reprinted with permission)

Figure 4.3 FKI Tower Exterior Wall Photo (©Adrian Smith + Gordon Gill Architecture, reprinted with permission)

Solar Concentrators

Photovoltaic systems have largely emerged as energy production systems of choice in many 'green' building projects. In highly urbanised environments, however, little roof area may be available for PV installations and the morphology of the urban environment itself poses significant challenges to the installation of traditional PV systems (Moraitis et al., 2018). BIPV offer advantages for urban situations by using the space offered by necessary building elements, but the need to seamlessly integrate these into buildings for aesthetic reasons has led to an interest in solar concentrators as a way to increase the concentration of solar energy reaching the PV cells (Debije and Verbunt, 2012; Hughes et al., 2020).

Traditional solar concentrators often rely on the concentration of direct solar energy and can be complex and require a large area reducing their attractiveness. A variety of alternative solar concentrators have been investigated, e.g. holographic solar concentrators (Marín-Sáez et al., 2019), luminescent solar concentrators (LSC) (Debije and Verbunt, 2012), or layered systems (Yupeng et al., 2016). Such systems can utilise direct, indirect or reflected light which reduces the need for solar concentrators to track the sun in the sky thereby reducing their cost and complexity. Such systems can use glass (or polymer) window systems to generate electricity from sunlight when attached to a PV cell, effectively turning otherwise passive glazed façades into electrical power generators.

An example of solar concentration as built into a structure is illustrated in Figure 4.4. This is another aspect of exterior wall system of the FKI Tower in Seoul, Republic of Korea, (Design Architects and Design Firm: Adrian Smith + Gordon Gill Architects), where solar concentration by façade design is used to reflect solar energy to the BIPV, as well as to facilitate natural lighting.

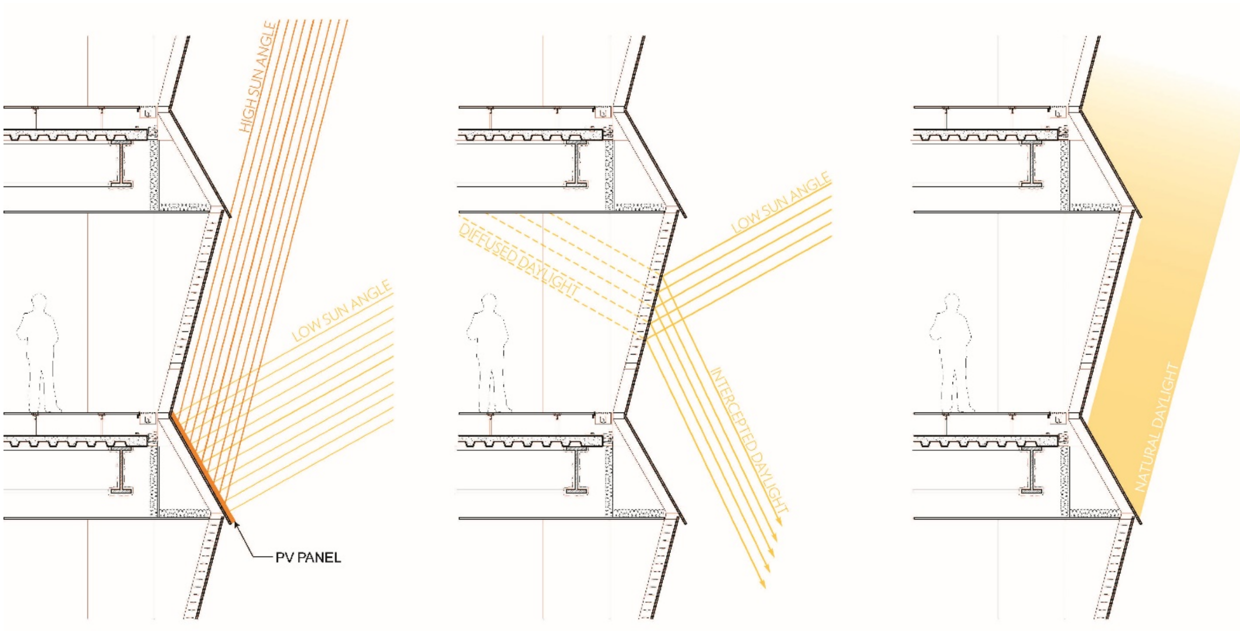


Figure 4.4 FKI Tower Exterior Wall Design – Solar Concentration and Reflection (©Adrian Smith + Gordon Gill Architecture, reprinted with permission)

While only one solar concentrator related fire incident was identified in this information search (Panepinto, 2019 (updated); 2012 (posted)), the hazards could be similar to melting of siding due to solar reflection from windows and other surfaces (Hart et al., 2011), and similar to BIPV system hazards noted above.

Energy-Related Fire Load/Hazards

Not only buildings material and systems include new 'green' technology as society shifts towards increased sustainability. New systems with implications for fire safety are often included in 'green' building design, e.g. the provision of charging stations for fully electric (EV) of plug-in hybrid (PHEV) vehicles. Similarly, other types of 'green' technology may be encouraged through the provision of company cars with alternative 'green' fuel technologies such as propane or natural gas vehicles, ethanol vehicles and fuel cells.

In particular, the number of electric vehicles (EV or PHEV) has increased significantly in recent years. Much work has been conducted to ensure safe vehicle technology, performance and safety standards development both for the vehicles themselves and for charging stations (Wang et al., 2019; Brandt and Glansberg, 2020), not least in large scale parking garage scenarios.

4.5 Structural Materials and Systems

Lightweight / Engineering Lumber Systems

Concerns with lightweight engineered lumber (LEL) include decreased thermal resistance to fire and contribution to fuel load. This was introduced in the 2012 report (Meacham et al., 2012), citing various studies, including those by UL Inc. and NRC Canada regarding fire performance of lightweight and engineered joists, trusses and floor systems, and times to failure compared with traditional sawn timber construction if not protected. Since then, different types of technologies and connections associated with lightweight lumber systems have been identified as potential concerns, particularly for responding firefighters (Shafer, 2013a; Shafer, 2017a; Shafer, 2017b; Shafer, 2018). As noted in 2012, concerns may exist if these systems are not adequately fire protected.

Since 2012, additional testing has been undertaken in Canada on lightweight lumber framing with respect to increasing building heights and areas, i.e., mid-rise buildings (see summary of tests in Su and Lougheed (2014), which also includes cross laminated timber (CLT) testing for midrise buildings). The findings demonstrated that an encapsulation approach is successful in delaying the time at which the wood structural elements are affected by and eventually contribute to the growth and spread of fire, if at all. It was noted, however, that the lightweight frame test results suggest that encapsulation should be addressed using a system approach, ensuring the junctions between the assemblies do not become the weak points for fire penetration. See also chapter 8 for discussion related to protection of lightweight timbe buildings during construction.

Mass Timber Construction

Large cross-sectional timber has been used as a primary framing mechanism for centuries. More recently, however, a new generation of engineered 'heavy' timber systems, broadly referred to as 'mass timber', is becoming widely accepted and used. As used here, mass timber systems includes glue laminated timber (glulam), cross laminated timber (CLT), nail laminated timber (NLT), dowel laminated timber (DLT), laminated veneer lumber (LVL) and laminated strand lumber (LSL), along with wood and concrete composite systems and construction. Mass timber has received much attention as it is perceived to be more sustainable than many other construction materials, see for example Osborne et al. (2012); Ruuska and Häkkinen (2014); Lineham et al. (2016); Suzuki et al. (2016); Crawford and Cadorel (2017); Hoehler et al. (2018); Dârmon and Lalu (2019); Muszyński et al. (2019) and publications through the websites cited below. Also, there was a strong drive to have exposed timber interior finish for aesthetic purposes from the architectural community.

The potential for using mass timber systems in larger and taller buildings to achieve these objectives triggered considerable research into fire performance of such systems. Europe was a region in which mass timber began to receive significant attention in the early 2000s (see for example Hakkarainen (2002), Frangi et al. (2008) and Kippel et al. (2014)). Motivation to use more timber in construction was seen in Japan in the early 2000s as well, which triggered research into fire performance of large timber buildings. Hagiwara et al. (2014b; 2014a) overview a set of large-scale wooden school building tests in Japan, and Suzuki et al. (2016) identifies some of CLT component testing in Japan. In North America alone, research efforts significantly increased over the last decade. The summary of work in Canada by Su and Lougheed (2014) provides a good overview. In addition, a significant number of reports on fire safety challenges to tall wood buildings can be found on the websites of the FPRF (FPRF, 2020), the American Wood Council (AWC, 2020b) and the Canadian Wood Council (CWC, 2020). A number of research reports are also available through the NIST publications web portal (NIST, 2020b) and the NRC Canada publications web portal (NRC, 2020a; NRC, 2020b; NRC, 2020c). Similar is true to various research organizations around the world.

While research and test programs such as these has demonstrated good fire performance under defined scenarios, with little challenge to structural resilience or fire spread if encapsulated, some concerns still remain, including connections, penetrations and cavities (void spaces), and where exposed timber is still desired. In medium and high rise buildings, where there is a requirement for a structure to survive burn out of the fire, this can be very challenging to achieve. Researchers are looking at aspects like "self-extinguishment" of mass timber. However, there are physical challenges to this, in particular for fire compartments with larger areas of exposed mass timber, and fire service intervention may be needed. The issue of designing for a decaying fire suggests that mass timber buildings may currently be held to a higher standard of performance than some steel or concrete structures (e.g., see outcomes of recent concrete and steel composite beam tests (Selvarajah et., 2020; Choe et al., 2020; 2020a)). Also, issues of fire dynamics within large compartments (>1000m2) is still unknown, and there is very limited fire testing available for exposed mass timber. Fundamentally, goals regarding a structure being able to survive a fully developed fire through to decay have not necessarily been proven, particularly for high rise buildings. While this might be equivalent performance to a structural steel building, which could also fail with prolonged fires, it warrants further research.

Selvarajah Ramesh, Lisa Choe, Mina Seif, Matthew Hoehler, William Grosshandler, Ana Sauca, Matthew Bundy, William Luecke, Yi Bao, Matthew Klegseth, Genda Chen, John Reilly, Branko Glisic (2020). Compartment Fire Experiments on Long-Span Composite-Beams with Simple Shear Connections Part 1: Experimental Design and Beam Behavior at Ambient Temperature, NIST Technical Note 2054, https://doi.org/10.6028/NIST.TN.2054

Lisa Choe, Selvarajah Ramesh, Matthew Hoehler, Mina Seif, Matthew Bundy, John Reilly, Branko Glisic (2020). Compartment Fire Experiments on Long-Span Composite-Beams with Simple Shear Connections Part 2: Test Results, NIST Technical Note 2055, https://doi.org/10.6028/NIST.TN.2055

L. Choe, S. Ramesh, W. Grosshandler, M. Hoehler, M. Seif, J. Gross and M. Bundy. Behavior and Limit States of Long-Span Composite Floor Beams with Simple Shear Connections Subject to Compartment Fires: Experimental Evaluation. *Journal of Structural Engineering*. Published March 24, 2020. DOI: 10.1061/(ASCE)ST.1943-541X.0002627

Carbon Fiber Composites

Carbon fiber reinforced composites have gained broad application largely due to their high strength to weight ratio. Initially applications focused on the transport industry due to its lightweight and shape flexibility; but, increasingly carbon fibers are of interest in a variety of building applications (Richards, 2015). To date applications have largely focussed on renovations or retrofitting where carbon fiber reinforced composites are added to concrete columns or timber that is below performance as a cheap method to reach acceptable strength without major rebuilding costs (see e.g. Rescalvo et al. (2017), De Souza Sánchez Filho et al. (2018) and Alhawamdeh and Alqam (2020)). Despite the high strength to weight ratio, there are some challenges still to be resolved before carbon reinforced fiber composites can expect to meet broad construction applicability, e.g. degradation under the impact of UV light, thermal cycles and moisture exposure (Richards, 2015).

The use of carbon reinforced composited as reinforcement in concrete structures is also gaining some traction in recent years. Carbon rebars have the advantage over steel that they exhibit higher tensile strength, in particular relative to their specific weight and perhaps most importantly they do not corrode (Mechtcherine et al., 2020).

Fiber Reinforced Concrete

The annual production of concrete has been estimated to be in the order of 10 billion tons (2009) and is projected to double by 2050 (Jin et al., 2015). Concrete has been used as construction material since ancient times but fire spalling of concrete was first recorded in 1854 (Jansson, 2013). In the 1950's it was recognised that traditional concrete appeared to exhibit less fire spalling propensity than modern concrete. Numerous theories and mitigation strategies have been put forward to explain the increased risk of spalling in dense concrete relative to more porous versions, where the addition of polypropylene fibres seems to be the most effective way of reducing spalling in dense concrete. The physics involved in the spalling phenomenon is still not known in detail and prediction of spalling behaviour based on modelling cannot be a substitute for fire testing (McNamee, 2019).

While concrete has significant advantages as a construction material (e.g. in terms of strength and durability) it does pose significant challenges from a sustainability point of view, mainly due to the significant energy needed during the production stage. Significant effort has been expended to reduce the life-cycle costs of concrete using a variety of methods, e.g. the implementation of lean production (Wu and Feng, 2014), optimisation of mixture recipe (Kim et al., 2013), the inclusion of waste as supplementary cementitious materials and alternative aggregates (Jin et al., 2015), or the use of carbon based rebars as alternatives to traditional iron reinforcement (Carvelli et al., 2013).

A variety of fiber reinforcement is typically employed in concrete to produce desired material properties, including the reduction of the fire spalling propensity of certain concrete recipes. Fibers are typically divided into: metal, synthetic (plastic), glass and natural fibers. The use of natural fibers is most marginal due to concerns about long term performance in the light of possible degradation over time. A significant amount of research has focussed on different fibers (see for example Zhang et al. (2020), Mukhopadhyay and Khatana (2015) and references therein). The research has investigated both the size, aspect ratio and concentration to maximize desired performance. At present the guidance given in the Fire Safety Eurocodes regarding the use of fibres relates only the concentration (weight fraction) of polypropylene fibres to avoid fire spalling.

Ultra-High Performance Concrete (UHPC)

Note that some additional information concerning UHPC is included in the preceding section on *Exterior materials and systems*, while some information is repeated in both sections to make them fairly complete individually. Increasingly, research has investigated the potential to leverage the very high strength of ultra-high performance concrete (UHPC) to reduce the material use in building elements (Barbos et al., 2014; Kromoser et al., 2019). Very few fire resistance tests on loaded real elements made of UHPC exist, as the majority of such research done is still on the material level. Until sufficient performance data is available, either test data or real life data, the prediction of full scale fire performance will be mainly speculation. Interestingly, some recent research indicates that UHPC could be a suitable material for 3D printing as discussed in the next section (Gosselin et al., 2016).

Additive Manufacturing (3D Printing)

Additive manufacturing (also commonly called 3D printing) has been developed since the 1980s (Matias and Rao, 2014, Kamble et al., 2018). Early applications of 3D printing have focused on the production of components to allow the relatively low investment development of early prototype materials without the need for expensive investments in traditional industrial machines or tools. More recently, the technology has been applied to building applications where it is hoped that similar savings may be made in manufacturing costs (Delgado Camacho et al., 2018) or in building construction sustainability by reducing waste and material production emissions (Williams, 2019) and life-safety at construction sites (Tay et al., 2017). While many different types of 3D technologies exist, building construction applications have focused on cementitious building elements as bespoke construction elements or prototypes. The use of 3D printing in such applications has the potential to remove the 35-60% of the construction cost associated with in situ casting and formwork (Pshtiwan et al., 2019). The application of 3D printing in the construction industry is not, however, limited to cementitious materials and can include both polymer printing (including bioplastics) and metal printing or composited of different materials (Delgado Camacho et al., 2018, Williams, 2019).

Modular Construction

The terms 'modular construction' and 'permanent modular construction' (PMC) broadly refer to the process by which components of a building are prefabricated off-site in a controlled setting and then shipped to the project site and assembled (MBI, 2019b; AIA and NIBS, NA). For 'fully assembled' modules, the term prefabricated prefinished volumetric construction (PPVC) is used as well (BCA, 2020). Benefits include the ability to capture the efficiencies gained by integrating the processes and technologies of design, manufacturing, and construction, without having to compromise on aesthetic intent, resulting in higher-quality buildings, delivered in a shorter time frames, with more predictable costs, and fewer environmental impacts. including through reduced material use and waste (AIA and NIBS, NA). Such buildings can be constructed of wood, steel, or concrete. Industry assessments reflect an increased use of modular construction over the past 3 years, and project even higher use in the coming 3 years (Buckley et al., 2020). A significant driver is cost savings (Bertram et al., 2019; Buckley et al., 2020), with estimates of 20% in construction cost savings over traditional methods, and a potential market value on $130 Billion in Europe and the USA by 2030 (Bertram et al., 2019).

Figure 4.5 Precast Concrete Modular High-rise Construction in Singapore – Module Being Lifted into Place by Crane (Source: Brian Meacham)

4.6 Building Systems

Interior EV Chargers

In addition to EV batteries, the charging system can be prone to facilitating fire ignitions. As noted by Stephens et al. (2017) one of the seven primary categories of contributing factors to EV battery fires is external electrical causes (including external electrical short, overcharging or over-discharging). Krok (2018) reports that Ford recalled 50,000 EV charging cables over fire concerns. Stephens et al. (2017) also note that a contributing factor is external thermal causes, including exposure to high temperatures or charging at cold temperatures. While electrical safety codes provide for safe electrical installations, these studies suggest there could be potential fire concerns in unconditioned garages, when charging cables are inadequate, and when some part of the charging system fails.

Heat Pumps

There is some indication that transitioning to residential heat pump systems might play a role in reducing fire risk in domestic buildings. Sekizawa (2019) notes this as a contributing factor in fire reductions in Japan, as the heat pump systems began to replace space heaters and other less safe systems. No data on this for the US or other countries was noted, but it might be assumed a similar trend could be possible.

4.7 Site

Pedestrian and Bicycle-Friendly Streetscape as relates to Emergency Access

Sustainable building not only relates to individual buildings as there is a move to 'green' neighbourhoods or suburbs, or even 'green' cities. One aspect of providing a vibrant albeit dense city centre is to improve pedestrian and bicycle access, in many cases in conjunction with decreased motor vehicle access (Elhamy, 2012; Nawrath et al., 2019). This can cause problems for first responders, not restricted to firefighters but including police and healthcare personnel. Emergency access is an important consideration which needs to be taken into account while creating sustainable built environments.

Dockless Bicycles and Scooters

Increased digitalisation and reduced access to motorised vehicles for city dwellers has led to the emergence of new modes of transport. Car-pooling or car-sharing alternatives create new challenges with vehicles being housed in hubs with cooperative or commercial owners leasing the vehicles on short term rental through apps. Fire safety of such vehicles is governed by the same traditional requirements as other similar vehicles and does not pose significantly different risks relative to traditional rental companies.

Similarly, the emergence of dockless bicycles or electric scooters is becoming more common as part of the cityscape (Chen et al., 2020). These vehicles are also accessed through an app and paid for on a per mile basis. The vehicles could be available anywhere in the city and are left at the user's destination (within certain limits). Such vehicles are bound to increase and become an important part of city mobility in the future. The widespread use of these vehicles is relatively new and little information is available concerning fire incidents at present.

Densification

A sustainable development approach in many parts of the world is to increase the density of housing. In brief, the intent is to locate more people and services, in less space, in a more sustainable manner than might traditionally be the case. High density, or higher density, is therefore contextual (Haughey, 2005). Such higher density developments can be accompanied by mechanisms to reduce traffic, or traffic calming measures, which can include narrower streets, vertical deflections (speed humps), traffic circles and more (e.g., see the traffic calming eprimer developed by the US DOT, Federal Highway Administration, FHA (Undated)). In parts of the US, these higher density developments can be characterized by tightly spaced, timber-framed structures, in some cases with vehicle access only from the back (with building fronts facing each other across green space). While these aspects are likely addressed in planning, building and fire regulations, care is required to assure all components work together. For example, means to minimize fire spread along adjacent housing units should be assured. If traffic calming is in place, care should be taken to facilitate fire apparatus needs, including width, length, turning radius, vertical clearance and so forth. If vehicle access is from one side, means to facilitate firefighting from other sides may be needed.

Permeable Paving Systems

Permeable paving systems are designed to allow surface water to penetrate through or around the material into a base layer of stone and aggregate that can retain water until it can seep into the surrounding soil in such a way that there is little or no runoff. While designed to support vehicles (e.g., in a driveway), some applications may not contemplate a larger vehicle, such as fire apparatus. Design of such systems, as with the design of underground garages and similar spaces, where vehicle access is anticipated on the surface, should take into account fire apparatus size and weight issues.

Electric Vehicles (EV)

Batteries or electric vehicles (EV) including plug-in hybrid vehicles (PHEV) are also a potential concern. Electric Storage Systems (ESS) and Photovoltaic Systems (PVS) have been dealt with previously in this chapter. Electric vehicles add an additional risk in new buildings both due to the presence of the vehicles themselves and due to the installation of bespoke charging systems or their being connected overnight to house electricity in potentially unsafe ways. In modern domestic or business settings it is necessary to assess the increased installation of charging systems, changes in the fuel load and potential fire hazard associated with EVs.

Figure 4.6 Exemplar EV (Chevrolet Bolt) (Source: Brian Meacham)

Stephens et al. (2017) investigated Lithium-ion battery safety issues of electric and plug-in hybrid vehicles. They conclude that the risk of electrochemical failure and the propensity and severity of fires and explosions from accidental ignition of flammable electrolyte solvents used in Li-ion battery systems are anticipated to be somewhat comparable to or perhaps slightly less than for gasoline or diesel vehicles. They note seven primary categories of contributing factors:

- External electrical causes (including external electrical short, overcharging or over-discharging)
- External thermal causes (including exposure to high temperatures or charging at cold temperatures)
- External mechanical causes (including excessive shock, impact, compression (crush) or penetration)
- External chemical contamination (including penetration of packaging by water)
- Service-induced stress and aging that lead to electrochemical component breakdown
- Cumulative abuse and services causes resulting from the above
- Errors in design, manufacturing, operation and maintenance

Sun et al. (2020a) overview representative incidents and discuss the fire hazards and risks. They also note that EV fire is harder to suppress because of the potential re-ignition of battery and the difficulty in cooling the battery pack inside, and that while water is still considered as most effective, a significant amount of water is required to extinguish and cool the battery, unless it can be directly applied to the battery pack. Such hazards have been known for some time, with organizations such as the Fire Protection Research Foundation supporting research into hazards and firefighter response (Klock, 2013; Long Jr et al., 2013). However, with the growing number of EVs, this could be a growing concern, both on the road, as well as in parking structure (Boehmer et al., 2020).

Alternative fuel vehicles

Whereas previously petrol or diesel driven vehicles dominated the fleet of vehicles being parked in domestic situations (whether single residence or multi-residence), alternative fuel vehicles are becoming increasingly common. The inclusion of EV/PHEV in such settings is discussed above but other types of vehicles can be seen as 'green' technology, e.g. propane fueled vehicles, ethanol vehicles and hydrogen fuel cell vehicles. Additional technologies may be developed in the future of which we are unaware today. Parking of mixed fleets of vehicles may offer new hazards which should be considered when assessing the fire risk of 'green' development.

4.8 Hazard / Risk Assessment Tools for 'Green' Attributes in Buildings

This section considers hazard and/or risk assessment concepts, approaches and tools, which are applicable to 'green' attributes in buildings that have been developed since the original work was completed.

A conceptual model for comparative fire risk assessment, in which the change in relative risk associated with 'green' attributes in buildings was developed by as part of research into the quantification of 'green' building features on firefighter safety (Meacham et al. (2017). A comparative approach was selected due to the difficulty in conducting an exact or absolute fire risk assessment for a 'green' building feature given the lack of an agreed reference system and fire performance data. In this approach, only features that are common to both 'green' buildings and traditional buildings are considered in the comparative fire risk assessment tool, so as to provide the differential risk estimate. Furthermore, the focus is on occupant risk and firefighter risk. A schematic of the system is provided in Figure 4.4.

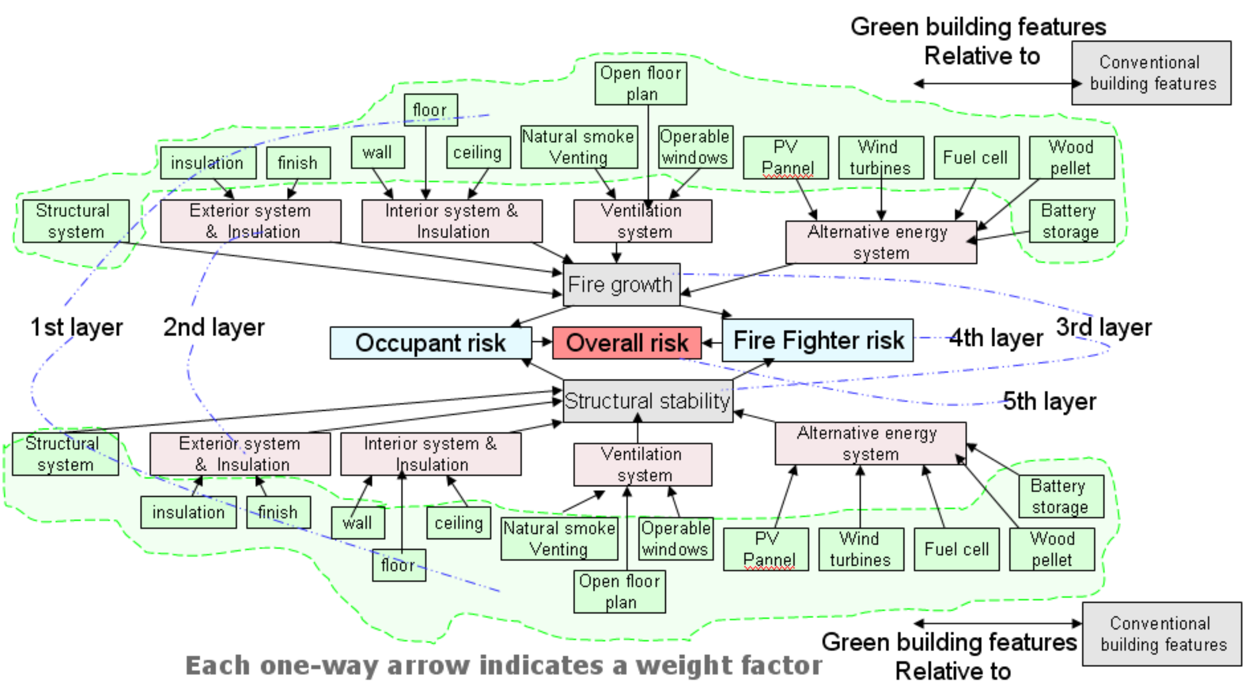


Figure 4.7 Schematic of Comparative Risk Assessment Approach for 'Green' Buildings (Meacham et al., 2017)

The approach was designed with the goal of giving users a clear delineation on the building risk, with a specific emphasis on the differences between new materials and methods and more traditional buildings, given various fire scenarios. The tool takes advantage of the risk indexing technique, such as underpins NFPA 101A, the Fire Safety Evaluation System (NFPA, 2019a) and the tool described by the fire risk tool for multi-story apartment buildings (Hultquist and Karlsson, 2000). In the approach, the analytical hierarchy process (AHP) (Saaty, 1986) was applied for assigning weights among layers.

A 'proof of concept' example demonstrated that the relative life safety risk to occupants and to firefighters can be quantified using a relative risk index approach and compared using relative weighting of the contributions of 'green' features to the risk estimate. While the approach has been shown to provide reasonable outcomes, the authors note that more data and testing are needed before it can be used in a meaningful way. Data from statistics, testing and expert judgment is needed to expand and increase the reliability of scores for elements in the model and the weights among layers.

Following the Grenfell Tower fire in London, England, in June 2017, the National Fire Protection Foundation (NFPA) developed the External Façade Fire Evaluation and Comparison Tool (EFFECT) based on sponsored research conducted by Arup, with peer review and technical input from Jensen Hughes, and input from a project technical panel (NFPA, 2018a). The EFFECT is based on a fire risk assessment (FRA) tool designed to provide a framework to aid authorities having jurisdiction (AHJ) to prioritize buildings in their jurisdiction and to conduct fire risk assessments of each building (Lamont and Ingolfsson, 2018). The tool provides a range of possible mitigation measures to help the AHJ and building owner to begin reducing the fire risk where deemed appropriate. The scope of the FRA tool is for high rise buildings, comprising residential or business occupancies or a mix of both, having steel or concrete structural frames, with a particular focus on façade systems. The tool is not applicable to timber frame buildings and is not designed to address all possible combinations of façade system and building characteristics. Some buildings cannot be readily assessed using the tool due to such factors as the complexity of the building, complexity of the façade patterns across the building, and difficulties in identifying the façade systems/materials/components. The FRA tool is qualitative in nature and builds upon the concepts described in PAS79 (BSI, 2012) in the context of a fire spreading over multiple stories of a building via a combustible façade system. Weighting of variables in the assessment is conducted using analytical hierarchy process (AHP) (Saaty, 1986). The AHP has been applied to risk characterization for use in building regulations previously (e.g., Meacham (2000b)). Details regarding the underpinning theories, data and assumptions in the FRA tool can be found in Lamont and Ingolfsson (2018).

While not developed specifically to assess risk associated with 'green' building features, the National Association of State Fire Marshal (NASFM) developed the MATRIX™ Fire Risk Evaluation tool (the MATRIX™) to assess the level of fire risk in existing buildings (MATRIX, 2020; NASFM, 2020). The MATRIX™ is a fire risk indexing tool for fire departments and others to use in determining the fire and life safety risk of a building (PG Public Service, 2017). As a baseline, this tool uses the specifications as detailed in Chapter 14 of the 2015 Edition of the International Existing Building Code (IEBC) as published by the International Code Council (ICC, 2015). The baseline specifications, which consist of a series of equations, parameters, conversion tables, and cross references, are integrated into the tool, which has an online questionnaire for use by fire and building inspectors to input data. The tool then calculates safety scores for the building.

While other fire risk assessment approaches were identified in the review, none were identified which focused specifically on 'green' building features and technologies. However, several works note the need for further development of such tools (e.g., Cancelliere and Castello (2013); Lamont and Ingolfsson (2018); van Hees et al. (2020)).

5. 'Green' Attributes and Potential Fire Hazards

This chapter presents lists of 'green' (sustainable) attributes (materials, systems and features) and potential hazards and risks associated with them. The starting point was the 2012 FPRF report (Meacham et al., 2012) as supplemented by research reflected in Chapter 4, and items for consideration as noted by the Project Technical Panel. While the lists provided are extensive, they may not be exhaustive, and it is recommended that the lists be updated by future studies as knowledge of other 'green' materials, features, elements and attributes, and associated potential hazards, is identified.

5.1 'Green' attributes

The 'green' attributes identified in this study, that may be incorporated into buildings and building sites, are presented in Table 5.1. To help facilitate comparison with the 2012 report, the groupings of materials, systems and features largely remain the same, e.g., *Structural Materials and Systems*, *Exterior Materials and Systems*, although the terms 'attributes' and 'issues' have been removed. Also, the relative location of the categories within the table have been shifted, and a few items have been relocated and/or combined for presentation purposes (e.g., battery and energy storage systems (ESS)).

The items identified in 2012 have been maintained. New items have been added. The new items are highlighted in pale green cell coloring. As presented here, there just over 100 'green' attributes, representing an increase of more than 20 from the 2012 report. Note that some 'green' attributes may be listed in more than one category, as they may have more than one use, or reflect more than one attribute. Examples include mass timber, which can present as *Structural Materials and Systems*, *Exterior Materials and Systems*, and *Interior Materials and Finish*. The expanded list of 'green' attributes is as follows. Note that for most new additions a short research review is provided in Chapter 4. Reference is made to the 2012 report (Meacham et al., 2012) for discussion on attributes not addressed in Chapter 4.

- Structural Materials and Systems
  - *Mass timber (e.g., CLT)*
  - *Additive manufacturing / 3-D printing*
  - *Inflated steel structure*
  - *Hempcrete*
  - *Ultra-High Performance Concrete*
  - *Carbon fiber composites*
  - *Modular construction*
- Exterior Materials and Systems
  - *Alusion Panels*
  - *PET for façade system*
  - *Interactive printed graphene*
  - *Novel biological materials*
  - *Building integrated carbon capture*
  - *Organic insulation*
  - *Composite window framing material*
  - *Mass timber & timber façade systems*
  - *Ultra-High Performance Concrete*
  - *Additive manufacturing / 3-D printing*
  - *Hempcrete*
- Interior Materials and Finish
  - *Mass timber (e.g., CLT)*
- Façade Attributes
  - *Out of plane geometries*
  - *Solar radiance concentration*
- Building Systems and Issues
  - *Interior EV chargers*
  - *Heat pumps*
- Alternative Energy Systems
  - *Battery / energy storage systems*
  - *Building integrated photovoltaics*
  - *Solar radiance concentration*
- Site Issues
  - *EES fuel loads / hazards*
  - *EV fuel load / hazards / chargers*
  - *Propane vehicle hazards*
  - *Fuel cell vehicle hazards*
  - *Bicycle storage impact exits*
  - *Reduced firefighter apparatus access*
  - *Densification / fire spread*

Table 5.1 'Green' (Sustainable) Attributes

Material / System / Feature	Material / System / Feature	Material / System / Feature
Structural Materials and Systems	Exterior Materials and Systems	Alternative Energy Systems
- Lightweight engineered lumber	- Structural integrated panel (SIP)	- PV roof panels
- Lightweight concrete	- Exterior insulation & finish (EFIS)	- Oil-filled PV panels
- FRP elements	- Rigid foam insulation	- Wind turbines
- Plastic lumber	- Spray-applied foam insulation	- Hydrogen fuel cells
- Bio-polymer lumber	- Foil insulation systems	*- Battery / energy storage systems*
- Bamboo	- High-performance glazing	- Cogeneration systems
- Phase-change materials	- Low-emissivity & reflective coating	- Wood pellet systems
- Nano materials	- Double-skin façade	*- Building integrated photovoltaics*
- Vegetative roof systems	- Bamboo, other cellulosic	*- Solar radiance concentration*
- Extended solar roof panels	- Bio-polymers, FRPs	Façade Features
- Mass timber (e.g., CLT)	- Vegetative roof systems	- Area of glazing
- Additive manufacturing / 3-D printing	- PVC rainwater catchment	- Area of combustible material
- Inflated steel structure	- Exterior cable / cable trays	- Exterior solar shades & awnings
- Hempcrete	- Exterior solar shades / awning	- Exterior vegetative covering
- Ultra-High Performance Concrete	- Exterior vegetative covering	*- Out of plane geometries*
- Carbon fiber composites	*- Alusion Panels*	*- Solar radiance concentration*
- Modular construction	*- PET for façade system*	Site
Interior Materials and Finishes	*- Interactive printed graphene*	- Permeable concrete systems
- FRP walls / finishes	*- Novel biological materials*	- Permeable asphalt paving / pavers
- Bio-polymer wall / finishes	*- Building integrated carbon capture*	- Extent (area) of lawn
- Bamboo walls / finishes	*- Organic insulation*	- Water catchment / features
- Wood panel walls / finishes	*- Composite window framing material*	- Vegetation for shading
- Bio-filtration walls	*- Mass timber & timber façade systems*	- Building orientation
- Glass walls	*- Ultra-High Performance Concrete*	- Increased building density
- FRP flooring	*- Additive manufacturing / 3-D printing*	- Localized energy production
- Bio-polymer flooring	*- Hempcrete*	- Localized water treatment
- Bamboo flooring	Building Systems	- Localized waste treatment
- Interior vegetation	- Natural ventilation	- Reduced water supply
- Skylights	- High volume low speed fans	- Hydrogen infrastructure
- Increased acoustic insulation	- Refrigerant materials	- Community charging stations
- Reflecting panels / solar tubes	- Grey-water for suppression	*- EES fuel loads / hazards*
- Mass timber (e.g., CLT)	- Rain-water for suppression	*- EV fuel load / hazards / chargers*
Interior Space	- On-site water treatment	*- Propane vehicle hazards*
- Tighter construction	- On-site waste treatment	*- Fuel cell vehicle hazards*
- Higher insulation values	- On-site cogeneration	*- Bicycle storage impact exits*
- More enclosed spaces	- High reliance on natural lighting	*- Reduced FD apparatus access*
- More open space (horizontal)	*- Heat pumps*	*- Densification / fire spread*
- More open space (vertical)	*- Interior EV charger*	*- EV chargers on building exterior*

5.2 Potential Hazards and Risks

In order to assess relative increases in fire hazard or risk or decreases in safety or performance of 'green' building features, attributes and technologies as compared with traditional construction, a list of risk, hazard or performance attributes of concern was required. The list in Table 5.2 was originally developed in 2012 (Meacham et al., 2012) from a combination of fire and life safety performance objectives typically addressed by building and fire codes and from issues identified during the literature review conducted at the time. The list has been reviewed as part of the current effort, and no additional attributes have been identified.

Table 5.2 Hazard, Risk and Performance Attributes

Poses potential ignition hazard
Poses potential shock hazard
Poses potential explosion hazard
Poses potential toxicity hazard
Readily ignitable
Burns readily once ignited
Contributes more fuel / increased heat release rate (HRR)
Material affects burning characteristics
Fast(er) fire growth rate
Significant smoke production/hazard
Potential for shorter time to failure
Failure affects burning characteristics
Failure presents smoke spread concern
Failure presents flame spread concern
Material presents flame spread concern
May impact smoke/heat venting
May impact occupant evacuation
May impact fire-fighter (FF) water availability
May impact suppression effectiveness
May impact fire apparatus access
May impact fire-fighter (FF) access and operations
May impact containment of runoff

It should be noted that the list reflects a focus on occupant and emergency responder safety issues and building performance issues. The list does not explicitly consider building contents protection, business continuity, or related market issues, which may also be of concern. While the list of attributes might be expanded or refined in the future, it provides a reasonable starting point and basis for comparative analysis.

The lists in Tables 5.1 and 5.2 were used in the development of the performance assessment matrix which could potentially be used as a checklist to help review a building plan, a building and/or a building site for potential risks or hazards, as well as a mechanism to reflect relative risk level associated with the 'green' building element.

6. Relative Hazard / Risk Assessment Frameworks

6.1 Original Frameworks

In the 2012 work (Meacham et al., 2012), the list of 22 potential fire hazards / risks associated and the 80 'green' building elements and attributes were combined into two different frameworks for communicating potential risk and risk mitigation: a 'relative risk matrix' and a table that presented 'relative concern level' and potential risk mitigation strategies. The intent was that these frameworks be used in support of relative hazard / risk assessments and as relative hazard / risk mitigation assessment, as well as communication tools. With respect to the 'relative risk matrix', it was suggested that this framework could serve as (a) a quick visual indication of how unmitigated 'green' features could pose specific hazards or risks, and (b) serve as a checklist of sorts for engineers, designers, insurers, authorities or others when reviewing site plans, building designs, renovation designs or buildings to guide inspection of 'green' attributes which could result in a fire hazard or building fire performance concern. An example of the original 'relative risk matrix' developed as part of the original work is shown in Figure 6.1.

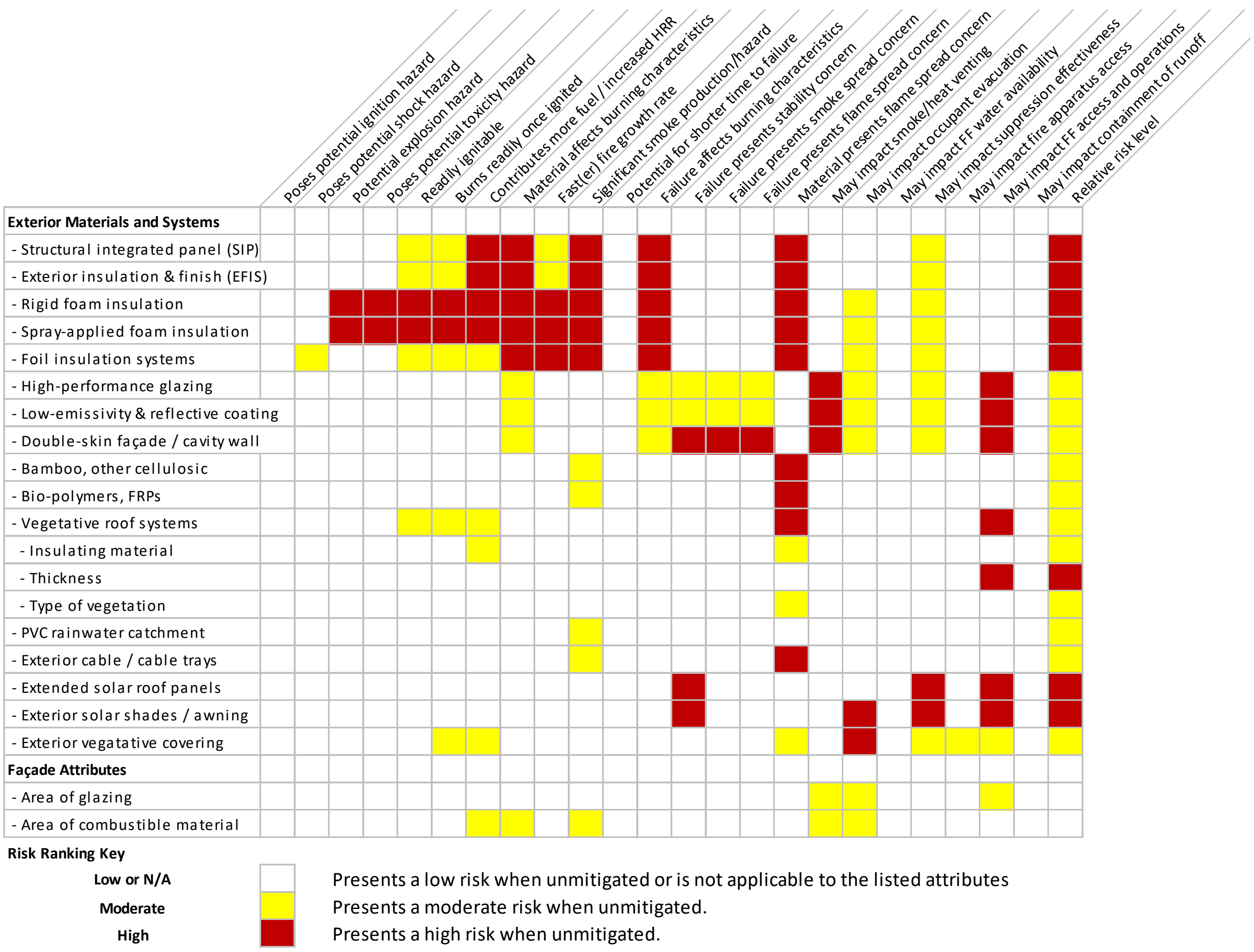


Figure 6.1 Relative Fire Risk/Hazard Level of 'Green' Attributes (Meacham et al., 2012).

In the 'relative risk matrix', the framing was a subjective assessment of relative risk, for each 'element' and 'hazard' pair, that reflected the statement: the relative risk of __, for the element __, if unmitigated, is low, moderate or high.

A similar approach was used for potential mitigation strategies. Here it was suggested that in many cases adherence with the existing test standards, codes and related design guidelines associated with traditional construction will help mitigate potential increases in fire risk or hazard associated with 'green' building elements. An example of the relative concern level and mitigation strategies framework is presented in Table 6.1.

Table 6.1 Tabular Representation of Attribute, Hazard, Concern Level & Mitigation (Meacham et al., 2012).

Material / System / Attribute	Hazard	Concern Level	Potential Mitigation Stratgies
Exterior Materials and Systems			
- Structural integrated panel (SIP)	If fail, insulation can contribute to flame spread, smoke production and fuel load.	High	Approved / listed materials. Assure proper sealing of panels. Take care during installation, including retrofits, relative to potential sources of ignition.
- Exterior insulation & finish (EFIS)	If fail, insulation can contribute to flame spread, smoke production and fuel load.	High	Approved / listed materials. Assure proper sealing of panels. Take care during installation, including retrofits, relative to potential sources of ignition.
- Rigid foam insulation	Can contribute to flame spread, smoke and toxic product development and fuel load.	High	Fire resistive barrier (e.g., fire rated gypsum). Approved / listed materials. Flame retardants. Sprinklers.
- Spray-applied foam insulation	Can contribute to flame spread, smoke and toxic product development and fuel load.	High	Fire resistive barrier (e.g., fire rated gypsum). Approved / listed materials. Flame retardants. Sprinklers.
- Foil insulation systems	Can contribute to shock hazard for installers. Can contribute to flame spread and fuel load.	High	Fire resistive barrier (e.g., fire rated gypsum). Approved / listed materials. Sprinklers.
- High-performance glazing	Can change thermal characteristics of compartment for burning. Can impact FF access.	Moderate	Sprinklers. Assure adequate FD access. Assure mechanism for FD smoke/heat venting. Approved / listed materials.
- Low-emissivity & reflective coating	Can change thermal characteristics of compartment for burning. Can impact FF access.	Moderate	Sprinklers. Assure adequate FD access. Assure mechanism for FD smoke/heat venting. Approved / listed materials.
- Double-skin façade	Can change thermal characteristics of compartment for burning. Can impact FF access. Can present 'chimney' for vertical smoke and flame spread if not properly fire stopped.	Moderate	Appropriate fire stop between floors. Sprinklers may have some benefit (sprinklered building). Assure mechanism for FD smoke/heat venting. Approved / listed materials.
- Bamboo, other cellulosic	Can contribute to flame spread, smoke development and fuel load.	Moderate	Approved / listed materials. Flame retardant treatments. Sprinklers.
- Bio-polymers, FRPs	Can contribute to flame spread, smoke development and fuel load.	Low	Approved / listed materials. Flame retardant treatments. Sprinklers.
- Vegetative roof systems	Can contribute to fire load, spread of fire, impact FF operations, impact smoke and heat venting, contribute to stability issues.	Moderate	Manage fire risk of vegetation. Assure use of fire tested components. Provide adequate area for FD acces, smoke/heat venting, and other operations.Approved / listed materials.
- PVC rainwater catchment	Can contribute additional fuel load.	Low	Limit volume.
- Exterior cable / cable trays	Can contribute additional fuel load.	Low	Limit volume.Approved / listed materials.
Façade Attributes			
- Area of glazing	Can present more opportunity for breakage and subsequent fire spread and/or barrier to FF access depending on type.	Moderate	
- Area of combustible material	Larger area (volume) provides increased fuel load.	High	Limit volume.
- Awnings	Impacts FF access.	Low	
- Exterior vegetative covering	Can impact FF access and present WUI issue.	Low	Limit volume.

6.2 Updated Relative Hazard / Risk Assessment Frameworks

This 2020 update reviews the original matrix and table, modifies the original information if appropriate based on the current research, and adds new materials, systems (technologies), features or attributes as identified. The 2020 color scheme has been normalized to red, yellow, while (high, medium, low) and 'green' shading for new items. Low, medium and high are subjective. In the updated matrices and tables presented in the next section they are based on the combined experience of the authors from almost 70 years of fire and combustion research.

As previously, the framing was an assessment of relative risk, for each 'element' and 'hazard' pair, that reflected the statement: the relative risk of __, for the element __, **if unmitigated**, is low, moderate or high. Therefore, these rankings are applicable only for a specific element across the range of hazards. It is also by necessity generalized to the attribute, and not specific to particular building characteristics (e.g., height, volume, etc.). This is due to the range in applications, uses and consequences associated with the risk (i.e., application in low-rise or high-rise building; risk of structural failure of a structurally integrated panel (SIP) is not compared to risk of fire / smoke spread within a double-skinned façade). A much greater level of data and information about materials, their properties, and use in a specific building context, and a more complex assessment tool, would be needed for such assessment. (This is noted as a need in Future Research.)

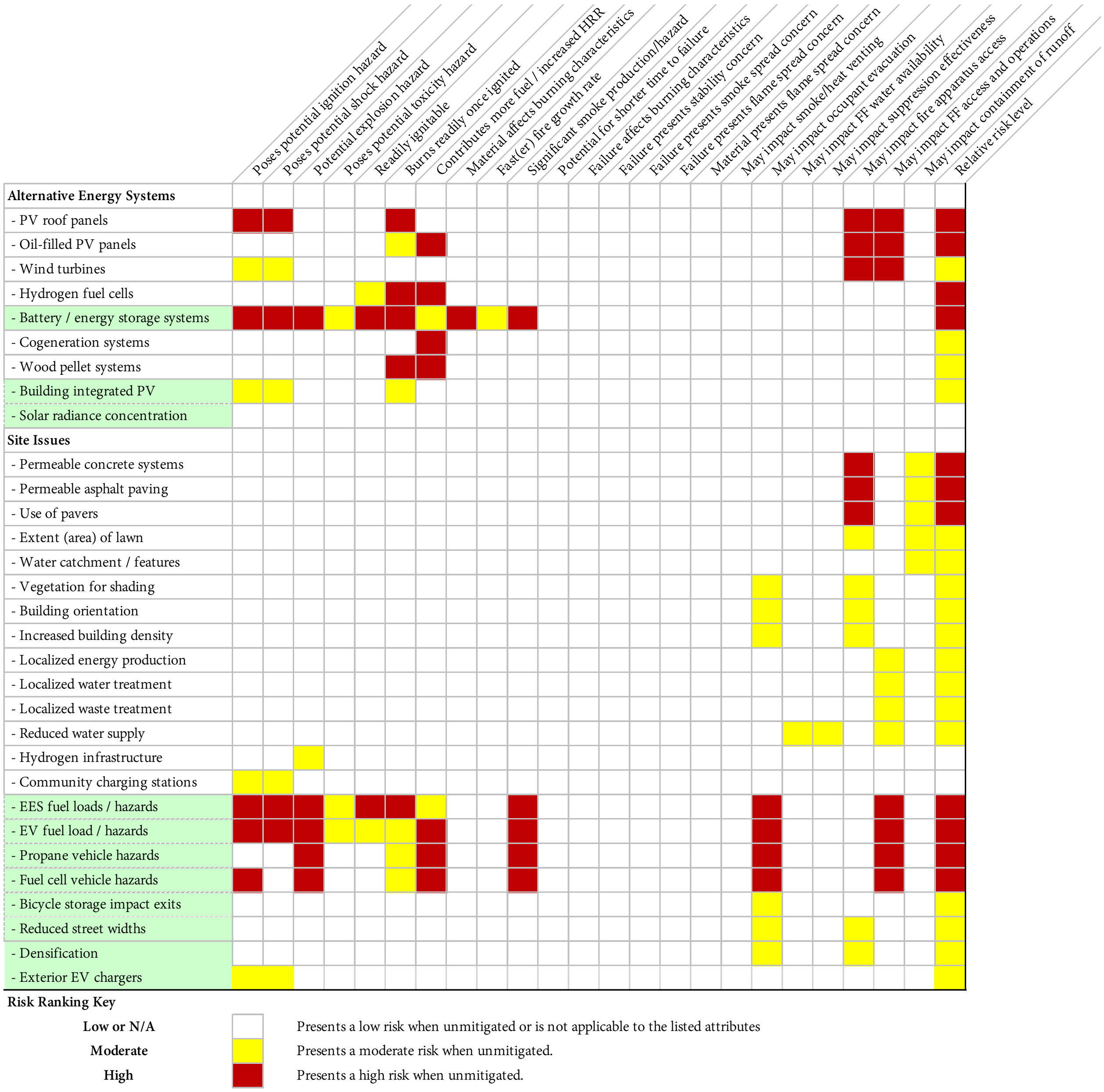
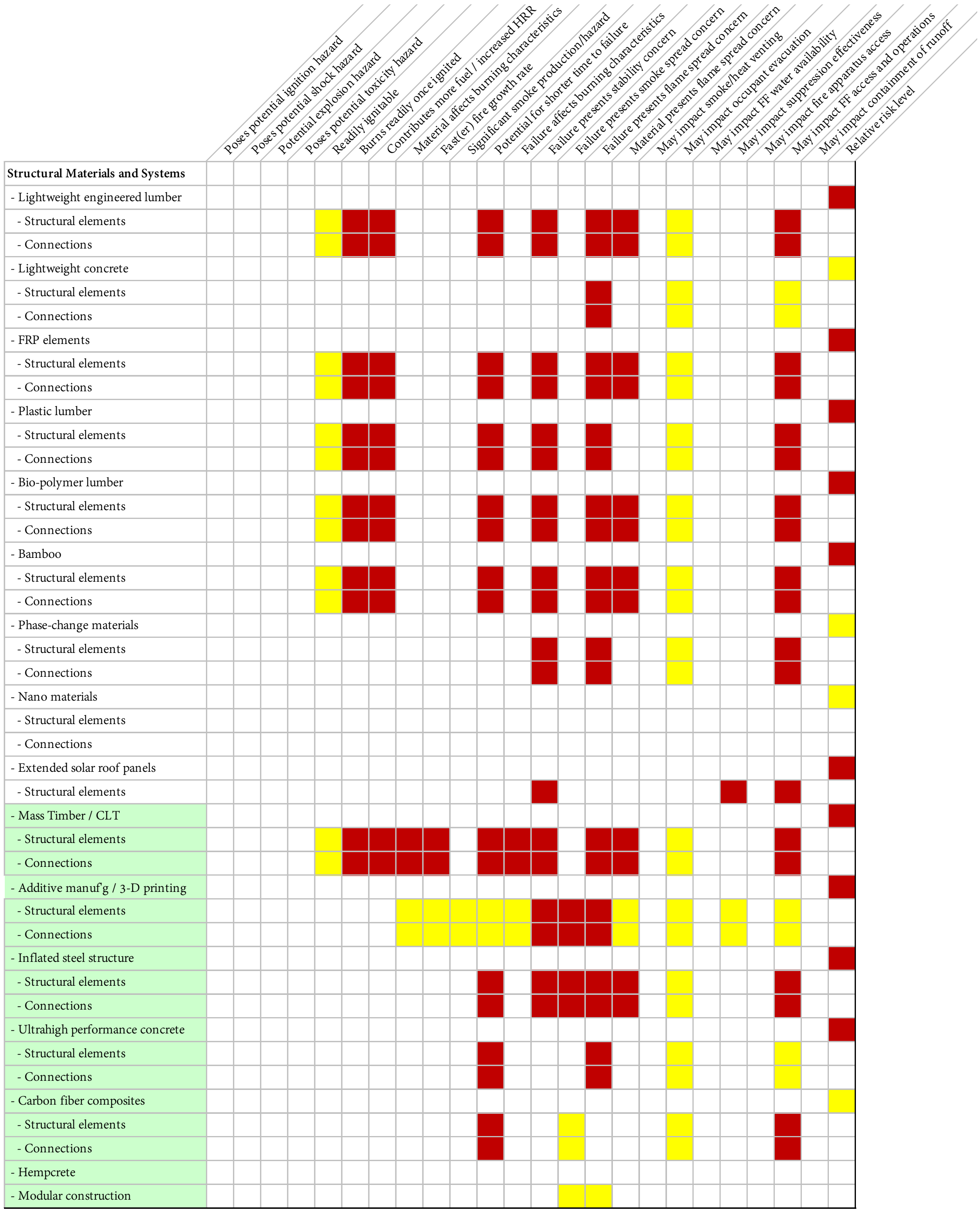


Figure 6.2 Relative Fire Risk/Hazard Level of 'Green' Attributes – Power & Site



Risk Ranking Key

Low or N/A	Presents a low risk when unmitigated or is not applicable to the listed attributes
Moderate	Presents a moderate risk when unmitigated.
High	Presents a high risk when unmitigated.

Figure 6.3 Relative Fire Risk/Hazard Level of 'Green' Attributes – Structure

Figure 6.4 Relative Fire Risk/Hazard Level of 'Green' Attributes – Exterior

Figure 6.5 Relative Fire Risk/Hazard Level of 'Green' Attributes – Interior & Systems

Table 6.2 presents the 'green' building attributes from 2012 plus the 2020 additions (additions highlighted in green). As in 2012, a tabular format is provided to include more information, including textual descriptions of the potential increased hazard or risk if unmitigated, and potential mitigation strategies to address the concerns. Note the color scheme was changed from the 2012 table to match the matrices (i.e., red being high, yellow moderate and low or unknown white).

Table 6.2. Tabular Representation of Attribute, Hazard, Concern Level and Potential Mitigation

Attribute	Hazard	Concern Level	Potential Mitigation Strategies
Structural Materials and Systems			
Lightweight engineered lumber	Can fail more quickly. Contributes to fuel load. Impact for egress and FF. Stability issues.	High	Fire resistive barrier (e.g., fire rated gypsum). Approved / listed materials. Sprinklers.
Lightweight high performance concrete	Can spall more explosively if not treated with fiber. Can fail more quickly. FF and stability issues.	Moderate	Require fibers for strength. Approved / listed materials.
FRP elements	Can fail more quickly. Contributes to fuel load. Impact for egress and FF. Stability issues.	High	Require formulations with high ignition temperatures, low flame spread and low smoke production; cover with thermal barrier or intumescing cover. Approved / listed materials.
Plastic lumber	Can fail more quickly. Contributes to fuel load. Impact for egress and FF. Stability issues.	High	Fire resistive barrier (e.g., fire rated gypsum). Approved / listed materials. Sprinklers.
Bio-polymer lumber	Can fail more quickly. Contributes to fuel load. Impact for egress and FF. Stability issues.	High	Fire resistive barrier (e.g., fire rated gypsum). Approved / listed materials. Sprinklers.
Bamboo	Can fail more quickly. Contributes to fuel load. Impact for egress and FF. Stability issues.	Moderate	Fire resistive barrier (e.g., fire rated gypsum). Approved / listed materials. Sprinklers.
Phase-change materials	Unknown	Unknown	Research and testing. Approved / listed materials.
Nano materials	Unknown	Unknown	Research and testing. Approved / listed materials.
Extended solar roof panels	Can create hazard to FF if fails. Impacts FF access.	Moderate	Provide fire proofing. Assure options for FF access. Approved / listed materials.
Mass timber (e.g., CLT)	Can delaminate. Contributes to fuel load. Stability issues.	High	Fire resistive barrier (e.g., fire rated gypsum). Approved / listed materials. Sprinklers.
Additive manufacturing / 3-D printing	Can include combustible material. Can fail more quickly. Impact for egress and FF. Stability issues.	High	Require fibers for strength. Approved / listed materials.
Inflated steel structure	Can fail more quickly. Impact for egress and FF. Stability issues.	High	Require formulations with high ignition temperatures, low flame spread and low smoke production; cover with thermal barrier or intumescing cover. Approved / listed materials.
Ultra-High Performance Concrete	Can spall more explosively if not treated with fiber. Can fail more quickly. FF and stability issues.	High	Require fibers for strength. Approved / listed materials.

Attribute	Hazard	Concern Level	Potential Mitigation Strategies
- Carbon fiber composites	Can fail more quickly. Impact for egress and FF. Stability issues.	Moderate	Fire resistive barrier (e.g., fire rated gypsum). Approved / listed materials. Sprinklers.
Exterior Materials and Systems			
Structural integrated panel (SIP)	If fail, insulation can contribute to flame spread, smoke production and fuel load.	High	Approved / listed materials. Assure proper sealing of panels. Take care during installation, including retrofits, relative to potential sources of ignition.
Exterior insulation & finish (EFIS)	If fail, insulation can contribute to flame spread, smoke production and fuel load.	High	Approved / listed materials. Assure proper sealing of panels. Take care during installation, including retrofits, relative to potential sources of ignition.
Rigid foam insulation	Can contribute to flame spread, smoke and toxic product development and fuel load.	High	Fire resistive barrier (e.g., fire rated gypsum). Approved / listed materials. Flame retardants. Sprinklers.
Spray-applied foam insulation	Can contribute to flame spread, smoke and toxic product development and fuel load.	High	Fire resistive barrier (e.g., fire rated gypsum). Approved / listed materials. Flame retardants. Sprinklers.
Foil insulation systems	Can contribute to shock hazard for installers. Can contribute to flame spread and fuel load.	High	Fire resistive barrier (e.g., fire rated gypsum). Approved / listed materials. Sprinklers.
High-performance glazing	Can change thermal characteristics of compartment for burning. Can impact FF access.	Moderate	Sprinklers. Assure adequate FD access. Assure mechanism for FD smoke/heat venting. Approved / listed materials.
Low-emissivity & reflective coating	Can change thermal characteristics of compartment for burning. Can impact FF access.	Moderate	Sprinklers. Assure adequate FD access. Assure mechanism for FD smoke/heat venting. Approved / listed materials.
Double-skin façade	Can change thermal characteristics of compartment for burning. Can impact FF access. Can present 'chimney' for vertical smoke and flame spread if not properly fire stopped.	Moderate	Appropriate fire stop between floors. Sprinklers may have some benefit (sprinklered building). Assure mechanism for FD smoke/heat venting. Approved / listed materials.
Bamboo, other cellulosic	Can contribute to flame spread, smoke development and fuel load.	Moderate	Approved / listed materials. Flame retardant treatments. Sprinklers.
Bio-polymers, FRPs	Can contribute to flame spread, smoke development and fuel load.	Low	Approved / listed materials. Flame retardant treatments. Sprinklers.
Vegetative roof systems	Can contribute to fire load, spread of fire, impact FF operations, impact smoke and heat venting, contribute to stability issues.	Moderate	Manage fire risk of vegetation. Assure use of fire tested components. Provide adequate area for FD access, smoke/heat venting, and other operations. Approved / listed materials.
PVC rainwater catchment	Can contribute additional fuel load.	Low	Limit volume.
Exterior cable / cable trays	Can contribute additional fuel load.	Low	Limit volume. Approved / listed materials.
PET for façade system	PET can melt, contribute to flame spread, smoke production and fuel load.	High	Fire retardant additives. Noncombustible thermal barrier. Approved / listed materials.

Attribute	Hazard	Concern Level	Potential Mitigation Strategies
Interactive printed graphene	Can fail more quickly. Stability issues.	High	Fire retardant additives. Noncombustible thermal barrier. Approved / listed materials.
Plaited microbial cellulose	Can fail more quickly. Stability issues.	High	Fire resistive barrier (e.g., fire rated gypsum). Approved / listed materials. Flame retardants. Sprinklers.
Integrated carbon capture	Can include combustible materials, which can contribute to flame spread, smoke and toxic product development and fuel load.	High	Fire resistive barrier (e.g., fire rated gypsum). Approved / listed materials. Flame retardants. Sprinklers.
Organic insulation	Can include combustible materials, which can contribute to flame spread, smoke and toxic product development and fuel load.	High	Fire resistive barrier (e.g., fire rated gypsum). Approved / listed materials. Flame retardants. Sprinklers.
Composite window framing material	Can include combustible materials, which can contribute to flame spread, smoke and toxic product development and fuel load.	High	Fire resistive barrier (e.g., fire rated gypsum). Approved / listed materials. Flame retardants. Sprinklers.
Timber façade systems	Combustible. Can fail more quickly. Stability issues.	High	Fire resistive barrier (e.g., fire rated gypsum). Approved / listed materials. Flame retardants. Sprinklers.
Ultra-High Performance Concrete	Can spall more explosively if not treated with fiber. Can fail more quickly. FF and stability issues.	Moderate	Require fibers for strength. Approved / listed materials.
Façade Features			
Area of glazing	Can present more opportunity for breakage and subsequent fire spread and/or barrier to FF access depending on type.	Moderate	
Area of combustible material	Larger area (volume) provides increased fuel load.	High	Limit volume.
Awnings	Impacts FF access.	Low	
Exterior vegetative covering	Can impact FF access and present WUI issue.	Low	Limit volume.
Out of plane geometries	Can present opportunities for flame spread different to testing orientation. Can impact FF access.	High	Noncombustible materials. Consideration of external FF access.
Solar radiance concentration	Can present ignition hazard and/or glass breakage hazard on installed building, neighbor building, or other.	Moderate	Treatment of exterior surfaces relative to reflecting solar energy. Change orientation of building.
Interior Materials and Finishes			
FRP walls / finishes	Can contribute to flame spread, smoke development and fuel load.	Moderate	Approved / listed materials. Flame retardant treatments. Sprinklers.
Bio-polymer wall / finishes	Can contribute to flame spread, smoke development and fuel load.	Moderate	Approved / listed materials. Flame retardant treatments. Sprinklers.
Bamboo walls / finishes	Can contribute to flame spread, smoke development and fuel load.	Moderate	Approved / listed materials. Flame retardant treatments. Sprinklers.

Attribute	Hazard	Concern Level	Potential Mitigation Strategies
Wood panel walls / finishes	Can contribute to flame spread, smoke development and fuel load.	Moderate	Approved / listed materials. Flame retardant treatments. Sprinklers.
Bio-filtration walls	Can contribute to flame spread, smoke spread and fuel load.	Low	Approved / listed materials.
Glass walls	May not provide adequate fire barrier alone.	Moderate	Approved / listed materials. Sprinklers
FRP flooring	Can contribute to flame spread, smoke development and fuel load.	Low	Approved / listed materials. Flame retardant treatments. Sprinklers.
Bio-polymer flooring	Can contribute to flame spread, smoke development and fuel load.	Low	Approved / listed materials. Flame retardant treatments. Sprinklers.
Bamboo flooring	Can contribute to flame spread, smoke development and fuel load.	Low	Approved / listed materials. Flame retardant treatments. Sprinklers.
Mass timber (e.g., CLT)	Can delaminate, contribute to flame spread, smoke development and fuel load.	High	Fire resistive barrier (e.g., fire rated gypsum). Approved / listed materials. Sprinklers.
Interior Space Attributes			
Tighter construction	Can change burning characteristics of compartments. Can result in negative health effects, moisture and related issues.	Moderate	Assure adequate air changes and filtering. Approved / listed materials.
Higher insulation values	Can change compartment burning characteristics, result in additional fuel load and lead to impacts to FF access.	Moderate	Approved / listed materials. Sprinklers.
More enclosed spaces	Can result in challenges in finding fire source.	Low	Sprinklers.
More open space (horizontal)	Can contribute to fire and smoke spread.	Moderate	Sprinklers.
More open space (vertical)	Can contribute to fire and smoke spread.	Moderate	Sprinklers.
Interior vegetation	Can contribute fuel load. Can impact FF operations.	Low	Sprinklers.
Skylights	Can contribute to fire and smoke spread.	Low	Approved / listed materials. Sprinklers.
Solar tubes	Can contribute to fire and smoke spread.	Low	Approved / listed materials. Sprinklers.
Increased acoustic insulation	Can change compartment burning characteristics, result in additional fuel load and lead to impacts to FF access.	Moderate	Approved / listed materials. Sprinklers.
Building Systems			
Natural ventilation	Can impact ability to control smoke. Can influence smoke movement depending on environmental conditions.	Moderate	Dedicated smoke management system. Sprinklers. Dedicated FF smoke venting.
High volume low speed fans	Can influence sprinkler and detector performance.	Moderate	Additional sprinkler protection beyond code requirements.
Refrigerant materials	Can provide different burning, toxicity, and HazMat concerns.	Moderate	Approved / listed materials. Treat and protect appropriate to material hazards.
Grey-water for suppression	Can have impact of water availability for suppression. Could have impact	Low	Assure water is properly treated for use in sprinkler and standpipe system.

Attribute	Hazard	Concern Level	Potential Mitigation Strategies
	on MIC issues with sprinkler and hydrant systems.		
Rain-water for suppression	Can have impact of water availability for suppression. Could have impact on MIC issues with sprinkler and hydrant systems.	Low	Assure water is properly treated for use in sprinkler and standpipe system.
On-site water treatment	Can have impact of water availability for suppression. Could have impact on MIC issues with sprinkler and hydrant systems.	Low	Locate in fire rated construction or separate building. Sprinkler.
On-site waste treatment	Can create HazMat and containment issues.	Low	Locate in fire rated construction or separate building. Sprinkler.
On-site cogeneration	Can present new fire hazards.	Low	Locate in fire rated construction or separate building. Sprinkler.
High reliance on natural lighting	Can result in larger area of high-performance glazing.	Moderate	Consider including of battery powered emergency lighting.
PV exit lighting	Require permanent full lighting to charge material - if used with increased natural lighting may not be effective.	Moderate	Consider including of battery powered emergency lighting.
Reduced water supp. systems	Local restrictions or conditions (e.g., drought) may limit water available for suppression.	High	Include water storage within building / on-site to meet minimum FP needs.
Modular construction - cavities	Can provide pathway for spread of flame, smoke and toxic POC.	High	Fire seals. Encapsulation. Approved / listed materials.
Alternative Energy Systems			
PV roof panels	Presents ignition hazard and contributes to fuel load. Prevents shock hazard to FF. Presents glass breakage hazard.	High	Provide thermal barriers between PV cells and combustible roof material. Use noncombustible roof materials. Design roof space for FF access, heat and smoke venting. Have emergency power interruption. Clearly mark. Approved / listed materials.
Oil-filled PV panels	Presents ignition hazard and contributes to fuel load.	High	Provide thermal barriers between PV cells and combustible roof material. Use noncombustible roof materials. Design roof space for FF access, heat and smoke venting. Have emergency power interruption. Clearly mark. Approved / listed materials.
Wind turbines	Potential ignition hazard.	Low	Automatic and manual power interruption.
Hydrogen fuel cells	Presents explosion hazard and contributes to fuel load.	Moderate	Install in explosion vented or resistant enclosure. Leak detection and automatic shutoff. Clearly mark
Battery storage systems	Presents ignition hazard and contributes to fuel load. Source of potential shock hazard. My release corrosive or toxic materials if damaged.	Low	Provide adequate compartmentation and special suppression. Clearly mark. Approved / listed materials.

Attribute	Hazard	Concern Level	Potential Mitigation Strategies
Cogeneration systems	Additional fuel load.	Low	Provide adequate compartmentation and special suppression. Clearly mark.
Wood pellet systems	Additional fuel load.	Low	Sprinklers.
Electric vehicle charging station	Presents ignition hazard.	Low	Adequate shutoffs, shock protection. Clearly mark.
Tankless water heaters	May present ignition hazard.	Low	Smoke and CO alarms. Approved / listed materials.
Large energy storage systems	Presents ignition and explosion hazards, as well as contributes to fuel load. Source of potential shock hazard. May release corrosive or toxic materials if damaged.	High	Provide adequate compartmentation and special suppression. Clearly mark. Use approved / listed materials.
Building integrated photovoltaics	Can present ignition hazard and contributes to fuel load. Prevents shock hazard to FF. Presents glass breakage hazard.	High	Provide thermal barriers between PV system components and combustible building materials where possible. Have emergency power interruption. Clearly mark. Approved / listed materials.
Site Issues			
Permeable concrete systems	May affect pooling of flammable liquid and resulting pool fire, containment, runoff containment issues.	Moderate	Appropriate emergency response planning, including spill containment and suppression, and vehicle access.
Permeable asphalt paving	May affect pooling of flammable liquid and resulting pool fire, containment, runoff containment issues.	Moderate	Appropriate emergency response planning, including spill containment and suppression, and vehicle access.
Use of pavers	May affect pooling of flammable liquid and resulting pool fire, containment, runoff containment issues. May also have load-carrying issues wrt fire apparatus.	Moderate	Appropriate emergency response planning, including spill containment and suppression, and vehicle access.
Extent (area) of lawn	May present fire apparatus access challenges.	Low	Appropriate emergency response planning, including vehicle access.
Water catchment / features	May present fire apparatus access challenges.	Low	Appropriate emergency response planning, including vehicle access.
Vegetation for shading	May present fire apparatus access challenges.	Low	Appropriate emergency response planning, including vehicle access.
Building orientation	May present fire apparatus access challenges.	Low	Appropriate emergency response planning, including vehicle access.
Increased building density	May present fire apparatus access challenges. May increase fire spread potential.	Moderate	Appropriate emergency response planning, including vehicle access.
Localized energy production	May present more challenging fires for FD. May present access issues.	Low	Appropriate emergency response planning, including vehicle access.

Attribute	Hazard	Concern Level	Potential Mitigation Strategies
Localized water treatment	May present more challenging fires for FD. May present access issues. May impact runoff issues (may overload system with runoff).	Low	Appropriate emergency response planning, including vehicle access.
Localized waste treatment	May present more challenging fires for FD. May present access issues. May impact runoff issues.	Low	Appropriate emergency response planning, including vehicle access.
Reduced water supply	Local restrictions or conditions (e.g., drought) may limit water available for suppression.	High	Appropriate emergency response planning, including vehicle access. Consider local water supply (site or facility).
Hydrogen infrastructure	May present new and challenging fire and explosion hazards, putting several properties at risk depending on density.	Moderate	Appropriate emergency response planning. Appropriate shock protection. Suppression system.
Community charging stations	May present shock hazards for multiple users.	Low	Appropriate emergency response planning. Suppression system. Explosion venting/protection.
EES fuel loads / hazards	Presents ignition and explosion hazards, as well as contributes to fuel load. Source of potential shock hazard. May release corrosive or toxic materials if damaged.	High	Provide adequate compartmentation and special suppression. Clearly mark. Use approved / listed materials. Sprinkler garage.
EV fuel load / hazards	Presents ignition and explosion hazards, as well as contributes to fuel load. Source of potential shock hazard. May release corrosive or toxic materials if damaged.	High	Provide adequate compartmentation and special suppression. Clearly mark. Use approved / listed materials. Sprinkler garage.
Propane vehicle hazards	Presents ignition and explosion hazards, as well as contributes to fuel load. May release toxic materials if damaged.	High	Provide adequate compartmentation and special suppression. Clearly mark. Use approved / listed materials. Sprinkler garage.
Fuel cell vehicle hazards	Presents ignition and explosion hazards, as well as contributes to fuel load.	High	Provide adequate compartmentation and special suppression. Clearly mark. Use approved / listed materials. Sprinkler garage.
Bicycle storage impact exits	May present occupant egress and FD access challenges.	Low	Appropriate emergency response planning, including occupant egress and FF access.
Reduced street widths, barriered bicycle lanes	May present fire apparatus access challenges.	Low	Appropriate urban planning, including vehicle access.

7. Resiliency

The focus on sustainability in the built environment emerged about 40 years ago. The concept of resiliency of infrastructure and the built environment has existed for much longer, but 're-emerged' over the past twenty years. This chapter explores the relationship of sustainability and resiliency, and how thinking in terms of sustainable and fire resilient (SAFR) structures (and communities) can be beneficial. Note that the focus here is on resiliency to significant events, but that concepts of resiliency and durability, under normal building use, can be helpful to building performance and sustainability as well.

7.1 Resiliency and Sustainability – Similarities, Differences and Overlaps

There has been a widespread movement around sustainability in the built environment (sustainable development and construction) for more than three decades, arguably driven in the early days by the United Nation's World Commission on Environment and Development (otherwise known as the Brundtland Commission) report, *Our Common Future* (UN, 1987). With the soon to follow Intergovernmental Panel on Climate Change (IPCC) in 1988, the United Nations Framework Convention on Climate Change (UNFCCC) in 1992, and the Kyoto Protocol in 1997, there was a clear and global imperative to reduce carbon emissions. Early on it was identified that the built environment was responsible for a significant percentage of carbon emissions, driven largely by energy consumption but also embodied carbon. This awareness helped facilitate a wide range of energy use reduction guidance and requirements, from voluntary rating schemes (e.g., BREEAM (BRE, 1990), LEED (USGBC, 2000)) to regulation (e.g., the Energy Performance of Buildings Directive (EPBD, 2010; EPBD-rev, 2018)).

Resilience, as a design principle, was an implicit part of traditional construction knowledge before the 19th century, embodying such concepts as oversizing of components and spaces, redundancy, and reparability (Hassler and Kohler, 2014). Its meaning in design transformed over time with the creation of calculation methods for optimizing safety and use of materials to achieve required stability to static and dynamic forces (e.g., response to earthquake or wind forces). It took on new meaning relative to performance under extreme loading from such events as terrorist attacks and large hurricane events in the early 2000s (e.g., see Meacham and Johann (2006); McDaniels et al. (2008)), which then helped spawn the broader concepts of disaster resiliency (e.g., see NRC (2012); Cutter et al. (2013)) and community resilience (e.g., see NIST (2020a)). Resilience has now become intertwined with sustainability from the perspective of resilience of buildings and infrastructure to the effects of climate change. The Resilient Design Institute, for example, defines resilient design as "intentional design of buildings, landscapes, communities, and regions in order to respond to natural and manmade disasters and disturbances—as well as long-term changes resulting from climate change—including sea level rise, increased frequency of heat waves, and regional drought" (RDI, NA).

While the terms sustainability and resilience are widespread in the literature, there is significant variability in definitions and use of the terms. A review of the literature review was undertaken to explore similarities, differences and current management frameworks for increasing sustainability and resilience in an environmental management context (Marchese et al., 2018). The study found that sustainability was largely defined through the triple bottom line of environmental, social and economic system considerations, and that resilience was largely viewed as the ability of a system to prepare for threats, absorb impacts, recover and adapt following persistent stress or a disruptive event. It was found that three generalized management frameworks for organizing sustainability and resilience dominate the literature: (1) resilience as a component of sustainability, (2) sustainability as a component of resilience, and (3) resilience and sustainability as separate objectives. Regardless of the approach, however, implementations of these frameworks were found to have common goals of providing benefits to people and the environment under normal and extreme operating conditions, with the best examples building on similarities and minimizing conflicts between resilience and sustainability.

7.2 Sustainable and Fire Resilient (SAFR) Buildings

With respect to buildings, there is much in the literature about sustainable design, including several academic journals with a related focus (e.g., *Energy and Buildings* (Elsevier), *Building and Environment* (Elsevier), International *Journal of Sustainable Built Environment* (Elsevier), *Sustainable Cities and Society* (Elsevier), *Building Research and Information* (Taylor and Francis), *Sustainable Development* (Wiley)). Much of the literature focuses on reduction in energy use and material use, increased use of alternative and localized energy sources (e.g., PV systems, EES), and the like, although topics are incredibly diverse. Likewise, there considerable literature on resilient design of buildings and infrastructure (e.g., see Meacham and Johann (2006); McDaniels et al. (2008); Gernay et al. (2016)). However, this literature often focuses on resilience to specific hazards (e.g., seismic), or hazard typologies (e.g., natural events as compared with technological or terrorist events), with few specific discussions on fire resilient building design (Gernay et al., 2016). There is also growing literature about sustainable and resilient design, but here largely focused on natural hazard events, in particular events potentially driven by climate change, such as more extreme storms, drought and wildland fire (e.g., ESCAP (2012); Boyd and Juhola (2015); World Bank (2016); Gardoni et al. (2018)). Few references focused specifically on sustainability and fire hazard resilience for buildings were identified (Meacham, 2019).

Buildings can be designed to both be sustainable (in terms of use of resources) and to be resilient to natural and manmade disasters – including fire – as well as to long-term changes resulting from climate change. With respect to fire as a hazard, this type of thinking can result in SAFR (Sustainable And Fire Resilient) buildings / structures (Meacham, 2019). One representation of the intersection between sustainability and resiliency with respect to SAFR buildings is shown in Figure 7.1 below.

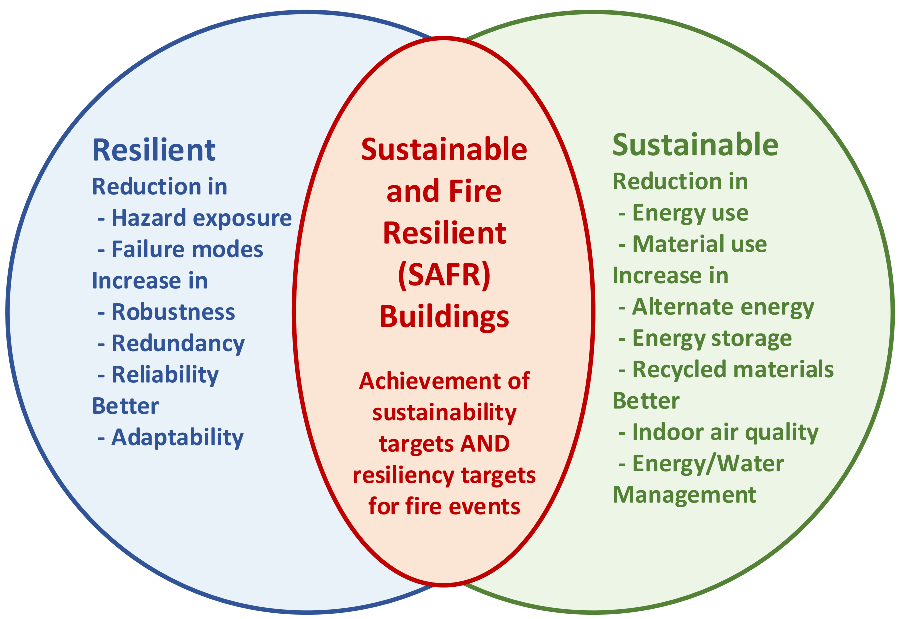


Figure 7.1 Sustainable And Fire Resilient (SAFR) Buildings Concept

The aim here is to develop and promote a holistic and integrated approach to achievement of sustainability and fire resiliency objectives in building design. This is seen to be extremely important, since some significant fires associated with 'green' building features, attributes and technologies have been observed, as reflected in Chapter 3. It is also important because, through the natural evolution of changes to building regulation, there has been some concern that fire resilience of buildings have decreased over time. The latter point was the impetus for the FAIL-SAFE project of the National Association of State Fire Marshals (NASFM, 2020). This project was designed to study the impacts on fire and life safety in structures equipped with multiple layers of both active and passive fire protection features to understand how active and passive fire protection features interdepend on one another in providing the level of safety the public and the fire service have come to expect. Research conducted as part of this project aims to provide quantifiable data to better understand the relationship between multiple layers of fire safety features and occupant survivability and to provide critical insight into methods of increasing building and business resiliency when exposed to the effects of a fire event.

As part of project FAIL-SAFE, research was conducted into fire protection system ‘trade-offs’ that have developed over time within building regulation, in particular the International Building Code (IBC) in the USA. Findings from the literature review include (Dembsey et al., 2017):

- many provisions in the current prescribed codes are empirical
- many sprinkler trade-offs are not based on scientific studies or analyses
- sprinkler trade-offs for fire resistance ratings are only partly supported by research using probabilistic risk analysis methods
- sprinkler trade-offs for an exterior wall’s unprotected opening area could be implicitly verified by fire tests designed to study the interactions of sprinklers with smoke layer behaviour
- sprinkler trade-offs for travel distance/dead end length are potentially not well founded as sprinklers fail to improve the tenability criteria of visibility, although sprinklers could be very effective in improving other tenability

While the study for the NASFM did not focus on ‘green’ building attributes, one could surmise that if there is a combination of reduced fire safety performance, coupled with added fuel loads and potential sources of ignition as associated with some ‘green’ building materials, systems or features, the combination could increase fire risk.

The specific issue of unintended consequences arising from focus on a single attribute of building performance, such as sustainability, without concurrent consideration of other important building performance objectives, such as fire safety, has been identified as a concern in the 2012 report on fire safety challenges of ‘green’ buildings (Meacham et al, 2012) and others (Meacham, 2014; 2016), and is reflected in some of the fire incidents and research identified in this current effort as discussed above. To recap a few, there can exist:

- potential fire and health hazards due to the flammability of thermal insulating materials,
- fire and smoke spread potential through the use of double-skinned façades,
- ignition and fire spread potential with a coupling of PV systems and combustible insulation,
- ignition, explosion and fire hazard potential associated with ESS and EVs,
- potential fire hazards and impediments to emergency responders associated with interior and exterior use of vegetation, PVS / BIPVS and other ‘green’ features and elements,
- potential fire hazards of exterior vegetation for shading or other in the wildland-urban interface,
- potential contribution of unprotected / inadequately protected LEL or mass timber to fire severity and potential structural failure, and
- increased potential of high strength lightweight concrete to spall during a fire and present potential for structural failure.

Several reasons for what and how potentially competing objectives have been introduced into the regulation and design of buildings, and the uneven levels of building performance that can result, have been identified (e.g., Meacham, 2016; Meacham and Stromgren, 2019), including changes in policy-level focus, a siloed approach to building regulation development and building design, lack of clarity between sustainability and resilience, introduction of new materials and systems without adequate testing and design understanding, and inadequate enforcement mechanisms. It has been suggested that in addition to a SAFR approach to building regulation and design, socio-technical systems (STS) thinking, and a STS approach for the whole of the building regulatory system is needed to adequately identify and manage competing objectives and deliver on holistic building performance (Meacham and van Straalen, 2017).

7.3 Holistic Socio-Technical Systems Approach for Sustainability and Resiliency

The literature suggests that there are no easy solutions for developing building regulatory systems and design approaches that are holistic and balancing of multiple objectives, such as sustainability and resiliency, since while the problems are easy to recognise, the solutions are difficult to agree and implement (Meacham, 2016). In many cases there is not a single policy area which has responsibility for avoiding or mitigating the impacts. Planning, zoning, environmental and resource legislation has a significant effect on the susceptibility of buildings to flooding and wildland fire (as is said in real estate valuation: location, location, location). In some cases, policy makers wish to avoid moving people or restricting expansion into hazard-prone areas if that has an impact on economic development. That places a burden on building regulation. Some of this can be addressed in regulations for new construction; however, affordability then becomes a concern. The challenges become even more amplified when addressing existing buildings, as there is less regulatory oversight and often less economic capacity to manage from the ownership side (i.e., older buildings, particularly residential, house a higher percentage of lower income families).

These challenges exist in part because sustainability and resiliency, in particular fire resiliency, are not yet being viewed as having the same level of importance, or equivalent level of social compact between government and the public, as providing for minimum levels of health and safety in buildings. As such, the rather sudden entry of new policy objectives around sustainability has created a wide range of fire resiliency challenges, from regulatory development to enforcement, to design, to operational safety, with potentially the most significant issues around existing building stock and trying to assure regulatory and market instruments adequately address the spectrum of policy objectives without increasing hazards, risks or costs, or decreasing building performance. The literature suggests that one step that can be taken towards resolving these challenges is better engagement of stakeholders, better characterization of use of risk and hazard data, and better clarification of roles, responsibilities and accountabilities of system actors through implementation of a socio-technical systems approach to building regulation and design of complex systems (Meacham and van Straalen, 2017; Meacham and Stromgren, 2019; van Hees et al., 2020).

Socio-technical systems (STS) theory and concepts emerged from studies of organizations and the roles of social and technological components and the realization that they are integrally linked, whether at an individual organizational level or as a collection of organizations and institutions operating at the overall level of society. It is from the societal level that the building regulatory system as a STS has been characterized, in particular the interaction of actors (stakeholders), institutions and innovation in defining and achieving acceptable building performance in both regulatory and market environments (Meacham and van Straalen, 2017; Meacham and Stromgren, 2019; 2019a). Research suggest that in times of rapid system change, either in regulation, technology or both, systems that are not structured to consider influence across the institutional or actor levels can lead to failures. In simple systems (regulatory or system design), prescriptive rules dominate, and adherence to the rules without deviation is likely and adequate. As complexity of the system increases, specification of every detail is difficult, as is striking the right balance with minimum requirements. This can lead to noncompliance with simple rules, or incomplete consideration of competing objectives. When this occurs, information associated with the deviations needs to get to the right people, who might be working within different parts of the systems, and this might not occur if the process is fast paced. In the end, as external factors influence the system at a faster pace than originally anticipated, the system may be ill-equipped to deliver on its target objectives. Thus, as building design, building systems (e.g., façade systems), and the building regulatory systems are challenged by multiple objectives, which are sometimes in competition, more holistic STS thinking maybe needed to deliver on buildings that meet the multiple societal expectations.

8. Regulations and Guidance

This chapter explores regulatory and guidance changes and new information associated with fire performance of 'green' building attributes since 2012. It also explores this situation with regulatory objectives for resiliency, and how better addressing sustainable and fire resilient performance could be helpful. Due to the extensive range of work conducted in this area since 2012, the primary focus is on the USA. However, reference is made to international standards and work in other countries, for most topics, to give an indication of the extent of international activities in this.

8.1 Photovoltaic Systems and BIPV

8.1.1 Standards

There are numerous consensus standards related to PV systems and components worldwide that reflect some aspect of fire safety. UK research into PV systems and fire (Pester et al., 2017) lists dozens of applicable standards, most of which promulgated by the International Electrotechnical Commission (IEC) Technical Committee (TC) 82, Photovoltaic Systems, but also those by the British Standards Institute (BSI), European Committee on Standardization (CEN), German Institute for Standardization (DIN), Australian / New Zealand Standards (AS/NZ), American Society for Testing and Materials (ASTM), National Fire Protection Association (NFPA, in particular the National Electrical Code (NEC)) and Underwriters Laboratories, Inc. (UL).

Similarly, a 2019 report from the International Energy Agency (IEA) explores requirements, specifications and regulations relevant to the development of BIPV performance and safety standards and provides information and proposals to support the development of international BIPV standards (Berger et al., 2019). This assessment considered largely standards developed by the IEC, the International Organization for Standardization (ISO), and CEN. From this, a needs analysis was undertaken, and requirements to fill gaps were identified. The findings suggest three levels of focus, "internationally mandatory," "useful to design BIPV" and "useful to characterize BIPV, but no need for pass/fail criteria" be addressed at the international standardization level. It was recognized that some technical requirements will continue to be addressed best at the national or local level, particularly if the topic is not of immediate urgency or that some non-technical requirements are beyond the scope of standardization efforts. Boddaert et al. (2019) point to many of these same issues.

In the USA, considerable work related to testing and standards for PV systems and fire have been undertaken. The Solar America Board for Codes and Standards has a website with summaries and links to several tests and standards (SABCS, 2015). This includes links to several reports, including testing that supported inclusion of a specific fire classification test into ANSI/UL (2013) *1703 Standard for Safety for Flat-Plate Photovoltaic Modules and Panels*. Scopes for all UL standards can be viewed by searching the on-line UL standards catalog at the UL Standards Catalogue (UL, 2020). FM Global also promulgates standards associated with PV systems. All FM approval standards are available for download at the FM Approvals Standards website (FM Approvals, 2020). Some National Fire Protection Association (NFPA) standards address PV systems as well.

Standards with a focus on PV systems include the following:

- ANSI/FM Approvals (2014) *4476 American National Standard for Flexible Photovoltaic Systems,* FM Approvals LLC, Norwood, MA, USA, 2014.
- ANSI/FM Approvals (2016) *4478 American National Standard for Roof Mounted Rigid Photovoltaic Modules,* FM Approvals LLC, Norwood, MA, USA, 2016.
- NFPA (2018b) 70E *Standard for Electrical Safety in the Workplace®,* National Fire Protection Association, Quincy, MA, 2018.

- ANSI/UL (2013) *1703 Standard for Safety for Flat-Plate Photovoltaic Modules and Panels*, Underwriters Laboratories, Inc., Northbrook, IL, 2013
- UL (2018) *1699B Standard for Photovoltaic (PV) DC Arc-Fault Circuit Protection*, Underwriters Laboratories, Inc., Northbrook, IL, 2018.
- UL 1897 (2015) Standard for Uplift Tests for Roof Covering Systems, Underwriters Laboratories, Inc., Northbrook, IL, 2015
- UL 7103 (2017) *UL LLC Outline of Investigation for Building-Integrated Photovoltaic Roof Coverings*, Underwriters Laboratories, Inc., Northbrook, IL, 2018

8.1.2 Codes / Regulations

There are various requirements around photovoltaics addressed in the following NFPA codes, which are available for free viewing online:

- NFPA 1 (2018), Fire Code, National Fire Protection Association, Quincy, MA, USA
- NFPA 70 (2020), National Electrical Code®, National Fire Protection Association, Quincy, MA, USA
- NFPA 5000 (2018), Building Construction and Safety Code®, National Fire Protection Association, Quincy, MA, USA

Within the International Code Council (ICC) family of codes, aspects of photovoltaics are addressed in the following documents:

- IBC (2018), International Building Code, Chapter 31 – Special Construction, Section 3111 – Solar Energy Systems, ICC, Washington, DC
- IFC (2018), International Fire Code, Chapter 12 – Energy Systems, Section 1204, Solar Photovoltaic Systems, ICC, Washington, DC

Local jurisdictions often have requirements as well.

- Los Angeles Fire Department Requirement No. 96, SOLAR PHOTOVOLTAIC SYSTEM, Los Angeles, CA (LAFD, 2014)
- Fire Department Reference Requirements For Rooftop Photovoltaic (PV) Systems on One and Two Family Dwellings, LAFD Bureau of Fire Prevention and Public Safety, Los Angeles, CA (LAFD, 2015)

While perhaps not strictly regulatory, various fire departments and related organizations have issue guidance and training for operations around PV systems. For example:

- *Solar Photovoltaic (PV) System Safety and Fire Ground Procedures*, San Francisco Fire Department, Division of Training, San Francisco, CA, USA (SFFD, 2012)
- The International Association of Fire Fighters (IAFF) offers an online Solar PV Safety for Firefighters Course to help first responders feel safe and cognizant of potential fire hazards when responding to fires on PV-equipped structures (IAFF, 2020)
- Firefighter Safety and Photovoltaic Systems, UL Firefighter Safety Research Institute report and on-line training (UL FSRI, 2020)
- On-line training for firefighters and code officials on solar energy systems, Interstate Renewable Energy Council, Latham, NY (IREC, 2020)

8.1.3 Guidance

There are numerous guidance documents available which touch upon fire safety issues with photovoltaics. By 'guidance' the focus is 'non-mandatory' from a regulatory perspective. Such documents may be published as guidelines for regulatory compliance, loss prevention information, recommended installation, test or maintenance practices, as part of research reports, as published articles and more.

A representative sample of guidance available in the USA includes:

- FM 1-15 (2014). Roof Mounted Solar Photovoltaic Panels, FM Global Property Loss Prevention Data Sheet, FM Global, Norwood, MA, USA.
- NFPA 70B (2019), *Recommended Practice for Electrical Equipment Maintenance* (Chapter 33), National Fire Protection Association, Quincy, MA, USA
- Sipe, J. (2016). Development of Fire Mitigations Solutions for PV Systems Installed on Building Roofs - Phase 1. Protection Research Foundation, Quincy, MA. (Sipe, 2016)
- Wills R., Milke, J., Royle, S. and Steranka, K. (2014). Commercial Roof-Mounted Photovoltaic System Installation Best Practices Review and All Hazard Assessment, Fire Protection Research Foundation, Quincy, MA, USA (Wills et al., 2014)

Guidance is also available for consumers, as published by government agencies and others promoting fire safety and PVS. For example:

- *A Consumer's Guide to Fire Safety with Solar Systems*, US Department of Energy (US DOE, 2020)
- CALSSA (2019). CALSSA Statement on Fire & PV System Safety, California Solar and Storage Association (CALSSA, 2020)

Guidance has also been published in other countries, such as in the UK (GOV.UK, 2017), Italy (e.g., (Cancelliere and Castello, 2013; Bonomo et al., 2017) and Switzerland (Muntwyler, 2016).

8.2 Energy Storage Systems

A recent article by Barowy (2019) overviews codes and standards relevant to ESS, with a focus on the USA. In the article, Barowy cites a 2014 inventory of codes and standards applicable to ESS safety (Conover, 2014), which identified 38 focused on ESS components, 36 applicable to the entire ESS (i.e., the system of interconnected components), 56 associated with ESS installation, 12 aimed at commissioning and maintenance, 8 associated with incident response and 3 for the transportation of ESS parts. Sections 8.2.1 and 8.2.2 below reflect the major codes and standards as summarized by Barowy (2019).

8.2.1 Standards

The following is a representative list of standards related to fire and explosion for ESS (Barowy, 2019).

- ASME TES-1 (2017), DRAFT TES-1 Molten Salt Thermal Energy Storage Systems, ASME Codes and Standards, New York, NY, 2017.
- IEEE C2 (2016), National Electric Safety Code (NESC), The Institute of Electrical and Electronics Engineers, Inc., New York, NY, 2016.
- NFPA 855 (2019). Standard for the Installation of Stationary Energy Storage Systems, Quincy, MA: National Fire Protection Association, September 2019.

- UL 9450A (2018). Test Method for Evaluating Thermal Runaway Fire Propagation in Battery Energy Storage Systems, Underwriters Laboratories, Inc., Northbrook, IL, 2018.
- UL 9450 (2016). UL Standard for Safety for Energy Storage Systems and Equipment, Underwriters Laboratories, Inc., Northbrook, IL, 2016.
- UL 1973 (2018). UL Standard for Safety for Batteries for Use in Stationary, Vehicle Auxiliary Power and Light Electric Rail (LER) Applications, Underwriters Laboratories, Inc., Northbrook, IL, 2018.
- UL 1974 (2018). Standard for Safety for Evaluation for Repurposing Batteries, Underwriters Laboratories, Inc., Northbrook, IL, 2018.
- UL 810A (2008). UL Standard for Safety for Electrochemical Capacitors, Underwriters Laboratories Inc., Northbrook, IL, 2008.
- UL 1741 (2010). Inverters, Converters, Controllers and Interconnection System Equipment for Use with Distributed Energy Resources, Underwriters Laboratories, Inc., Northbrook, IL, 2010.

A more complete review can be found in the Conover (2014) report. Updates on the ESS codes and standards is regularly provided through the Energy Storage Safety Collaborative (Sandia, 2020), including, Conover and Rosewater (2018); Conover (2019); Sokoloff (2020).

8.2.2 Codes / Regulations

The following is a representative list of codes / regulations related to fire and explosion for ESS (Conover and Rosewater, 2018).

- IFC (2018). *International Fire Code*, Section 1206, Electrical Energy Storage Systems, International Code Council, 2018.
- IRC (2017). International Residential Code, International Code Council, 2017.
- NEC (2017). NFPA 70, National Electrical Code, National Fire Protection Association, 2017.
- NFPA 1 (2018). National Fire Code, National Fire Protection Association, 2018.

The 2018 editions of NFPA 1 (2018) and the IFC (2018) contain updated safety requirements based on flow, lead-acid, lithium, Ni-Cd, and sodium chemistries. The IFC (2018) gives guidance on hazard mitigation analysis, protection measures, and requirements for construction documents. It is also worth noting that the IFC (2018) includes provisions on stationary fuel cell power systems (Section 2015).

Work has also been undertaken at the state level. A recent example is the New York State Energy Research and Development Authority (NYSERDA) *New York Battery Energy Storage System Guidebook for Local Governments* (NYSERDA, 2020). The Guidebook contains the following chapters:

- Battery Energy Storage System Model Law (Model Law): The Model Law is intended to help local government officials and AHJs adopt legislation and regulations to responsibly accommodate battery energy storage systems in their communities. The Model Law lays out procedural frameworks and substantive requirements for residential, commercial, and utility-scale battery energy storage systems.
- Battery Energy Storage System Model Permit (Model Permit): The Model Permit is intended to help local government officials and AHJs establish the minimum submittal requirements for electrical and structural plan review that are necessary when permitting residential and small commercial battery energy storage systems.
- Battery Energy Storage System Electrical Checklist (Checklist): The Battery Energy Storage System Electrical Checklist is intended to be utilized as a guideline for field inspections of residential and small commercial battery energy storage systems. It can be used directly by local code enforcement officers or provided to a third-party inspection agency, where applicable.

- 2019 Energy Storage System Supplement: The 2019 Energy Storage System Supplement amends the State's Uniform Fire Prevention and Building Code to implement the latest safety considerations for energy storage systems.

When combined with all applicable provisions of the codes, regulations, and industry standards as referenced in the New York State Uniform Fire Prevention and Building Code, these resources create an all-encompassing process to safely permit all types of battery energy storage systems (NYSERDA, 2020).

8.2.3 Guidance

In addition to codes and standards, there are numerous guidance documents available which touch upon fire safety issues with energy storage systems. By 'guidance' the focus is non-mandatory from a regulatory perspective. Such documents may be published as guidelines for regulatory compliance, loss prevention information, recommended installation, test or maintenance practices, as part of research reports, as published articles and more.

A representative sample of guidance available in the USA includes:

- Conover, D.R and Cole, P.C. (2016). *Energy Storage System Guide for Compliance with Safety Codes and Standards*, Report PNNL-SA-118870 / SAND2016-5977R, prepared for the U.S. DOE, Alexandria, VA.
- FM 5-33 (2017), *Electrical Energy Storage Systems*, FM Global Property Loss Prevention Data Sheet, FM Global, Norwood, MA, USA.
- Long, R.T., Jr. and Misera, A.M (2019). *Sprinkler Protection Guidance for Lithium-Ion Based Energy Storage Systems*. Fire Protection Research Foundation, Quincy, MA (Long Jr and Misera, 2019)
- NFPA 70B (2019), *Recommended Practice for Electrical Equipment Maintenance* (Chapter 33), National Fire Protection Association, Quincy, MA, USA
- NYSERDA (2020), *New York Battery Energy Storage System Guidebook for Local Governments,* New York State Energy Research and Development Authority (NYSERDA), Albany, NY.
- *Solar Photovoltaic (PV) System Safety and Fire Ground Procedures*, San Francisco Fire Department, Division of Training, San Francisco, CA, USA (SFFD, 2012)
- Siemens (2019). *Fire protection of Li-ion battery energy storage systems*, White Paper, Siemens AG, Germany.

8.3 Exterior Wall and Roof Systems

This section is divided into two parts – 'traditional' exterior wall and roof systems, and 'green / vegetative' exterior wall and roof systems. This division is made in order to highlight some changes made to standards, regulations and guidance following fires that have occurred in 'traditional' (i.e., non-vegetative) exterior wall systems with combustible components. Arguably a factor in some of the fires was combustible insulation added as part of 'green' or sustainability objectives, which is why the regulatory changes are highlighted here. The section on 'vegetative' systems reflects specific issues associated with incorporating living plants into the wall and roof systems.

8.3.1 Traditional Exterior Wall and Roof Systems

As reported in 2012, an increasing number of fires on exteriors of buildings had begun to emerge, involving such materials as structurally integrated panels (SIPs), metal composite panels (MCPs), and use of combustible insulation materials, rainscreen materials and the like (Meacham et al, 2012). As discussed in Section 3 of this report, there have been numerous fires involving exterior wall systems around the world, highlighted perhaps by the tragedy of the Grenfell Tower fire in England. As discussed in Section 4.2 of this report, the number of exterior wall fires triggered extensive discussion and research regarding fire performance of exterior wall systems, including the need for new or different test methods, need for regulatory change and more. This section discusses some of the key discussions and changes to date in the regulatory realm.

8.3.1.1 Standards

As discussed in Section 4.2, fire performance testing of façade systems has been conducted since the 1990's and numerous test methods have developed globally (Martinsson, 2018). As recently as 2016, the EU issued a tender asking for consortia to develop a pan-European approach to façade testing. The tender was awarded to a Consortium of five test labs across Europe under the leadership of RISE Research Institutes of Sweden. The final report from their work has recommended two test methods and a variety of performance criteria (Boström et al., 2018). Additionally, test methods are available in Canada (ULC, 2013) and the US (NFPA, 2017; NFPA, 2019c) or globally through the International Standardisations Organisation (ISO, 2002b; ISO, 2002a). A representative sample of fire test standards, applicable to exterior wall systems, is presented below. More extensive discussions can be found in the literature (e.g., Leško and Lopušniak (2016); Martinsson (2018); van Hees et al. (2020))

- ANSI/FM 4478 (2016). *Approval Standard for Roof-Mounted Rigid Photovoltaic Module Systems*, FM Approvals LLC, Norwood, MA, USA
- ANSI/FM 4880-2017 (2017). *American National Standard for Evaluating the Fire Performance of Insulated Building Panel Assemblies and Interior Finish Materials*, FM Approvals LLC, Norwood, MA, USA.
- ANSI/FM 4881-2017 (2017). *American National Standard for Evaluating Exterior Wall Systems*, FM Approvals LLC, Norwood, MA, USA.
- BS 8414-1 (2015). Fire performance of external cladding systems. Part 1: Test method for non-loadbearing external cladding systems applied to the masonry face of a building, BSI, 2015.
- BS 8414-2 (2015). Fire performance of external cladding systems, Part 2: Test method for non-loadbearing external cladding systems fixed to and supported by a structural steel frame, BSI, 2015.
- CAN/ULC-S134 (2013). Standard Method of Fire Test of Exterior Wall Assemblies. Canada: Standards Council of Canada.
- DIN 4102-20 (2017). Fire behaviour of building materials and building components - Part 20: Complementary verification for the assessment of the fire behaviour of external wall claddings. German Institute for Standardization (DIN).
- FM 4411 (2018). *Approval Standard for Cavity Wall Systems*, FM Approvals LLC, Norwood, MA, USA.
- FM 4450 (1989). *Approval Standard for Class 1 Insulated Steel Roof Decks*, FM Approvals LLC, Norwood, MA, USA.
- FM 4471 (2012). *Approval Standard for Class 1 Panel Roofs*, FM Approvals LLC, Norwood, MA, USA.
- FM 4478 (2016). *Approval Standard for Roof-Mounted Rigid Photovoltaic Module Systems*, FM Approvals LLC, Norwood, MA, USA
- ISO 13785-1 (2002). Reaction-to-fire tests for façades — Part 1: Intermediate-scale test. Geneva: ISO.
- ISO 13785-2 (2002). Reaction-to-fire tests for façades — Part 2: Large-scale test. Geneva: ISOBSI
- NFPA 268 (2017). Standard Test Method for Determining Ignitability of Exterior Wall Assemblies Using a Radiant Heat Energy Source. National Fire Protection Association. Quincy, MA, USA
- NFPA 285 (2019). Standard Fire Test Method for Evaluation of Fire Propagation Characteristics of Exterior Wall Assemblies Containing Combustible Components. National Fire Protection Association. Quincy, MA, USA.

8.3.1.2 Codes / Regulations

In the USA, one of the first 'wake-up' calls to the challenges of exterior wall fires was a 2007 exterior wall system fire at the Borgata Casino Hotel in Atlantic City, New Jersey, where considerable fire spread was observed on combustible cladding (White and Delichatsios, 2014). The 41-storey building was under construction and nearing completion, and was clad with an aluminium composite panel system having a polyethylene core. The fire initiated on the 3rd floor and rapidly spread vertically, reaching the top of the building on one side. While there were no deaths or injuries as a result of this fire, this fire began discussion about limiting the amount of combustible material in high-rise façade systems in the US building codes.

Several code change proposals were submitted to the International Code Council (ICC) code change process for the International Building Code (IBC), one of the model building codes in the USA, and several changes were adopted into the 2012 edition, many of which remain in place today (ICC, 2018a). The IBC limits combustible materials on exterior walls based upon the following factors:

- Type of exterior wall cladding.
- Type of construction of the building. Buildings of Types I – IV construction are required to have noncombustible exterior walls. However, these walls can have combustible exterior cladding, such as metal composite materials (MCM)s.
- Height of the cladding above grade. The installation height of combustible cladding on the exterior can have a considerable impact on firefighting operations.
- The presence of an automatic sprinkler system throughout the building. The IBC requires all new high-rise buildings (buildings with occupied floors greater than 75 feet above the lowest level of fire department vehicle access) to be protected throughout with an automatic sprinkler system.
- Percentage of the exterior wall covered with the combustible cladding.
- The required fire-resistance rating of the exterior wall.
- Fire separation distance of the exterior wall from adjacent buildings and lot lines.
- Fire testing for the specific type of exterior wall cladding.

The reader is referred to White and Delichatsios (2014) and ICC (2018a) and for more detailed discussions of the applicable provisions in the IBC.

Likewise, revisions were made to NFPA 5000, Building Construction and Safety Code (NFPA, 2019d), the model building code developed through the NFPA process. With respect to exterior fire performance requirements, the NFPA 5000 addresses many of the same areas as the IBC. A summary of applicable provisions can be found in White and Delichatsios (2014).

Regulatory change has also occurred in the Gulf Region following a number of high-rise façade fires over the past decade. For example, the 2018 UAE Fire & Life Safety Code of Practice (UAE, 2018) contains several improvements from the previous edition to more appropriately address exterior wall construction, including a robust combination of component level tests, large scale testing, and the requirement for third party certification (listing and labeling) of the products and systems to promote construction that resist the spread of fire, as we as a framework for materials to be identified for installation in a manner that represents testing and proper enforcement (UL, 2019). Some of the specific changes include (Vortex, 2018):

- Requirement of spandrels for all buildings except low rise and open parking structures. Previous concession for sprinkler protected buildings is not applicable as per the revised code.
- Balconies are required to be provided with fire sprinkler protection.
- GRC cladding is required to be tested as a product and assembly similar to ACP cladding.

- Emergency vehicular access required to at least 25% of tower perimeter when located above a podium.
- Reduced requirement for fire pumpsets and fire water storage duration.
- Concessions on fire protection of electrical and telephone rooms.
- Requirement for smoke detection and alarm system in private villas.

In addition, many building regulations from other countries, such as the IBC and NFPA 5000 may be permitted to be used in several countries in the region.

Fire performance of exterior wall systems garnered worldwide attention with the 2017 Grenfell Tower fire in London, England. Preceded by the 2014 Lacrosse Building fire in Melbourne, Australia, these fires triggered numerous regulatory reviews, including Metropolitan Fire Brigade (MFB, 2015), City of Melbourne (Genco, 2015), and Shergold and Weir (2018) investigations in Australia, the Hackitt review (MHCLG, 2017b; MHCLG, 2018b; MHCLG, 2018a) and public inquiry (Grenfell Tower Inquiry, 2020) into Grenfell Tower in England, and the Ministerial Review on Building Standards (Fire Safety) in Scotland (Stollard, 2018) are just a few examples.

With respect to the Grenfell Tower fire, from the very beginning attention was focused on the fact England operated under a functional-based building regulatory scheme, and questions were raised as to how this might have contributed to the significance of the fire (Meacham and Strömgren, 2019). Arguably, Australia and Scotland began reviews for similar reasons, as the Australian system is performance-based and the Scottish is functional-based (although different from England), and Australia had by some accounts narrowly avoided a 'Grenfell-type disaster' when the exterior cladding of the Lacrosse Building in Melbourne caught fire and burned up the side of the building, and post-incident investigations surrounding that event highlighted numerous building regulatory system concerns (Genco, 2015; MFB, 2015).

The current Building Regulations in England are function-based, and are supported by a set of Approved Documents (ADs), which are generally nonmandatory guidance that reflects one means of compliance with the Building Regulations. The ADs include reference to a number of consensus standards for testing, design, etc.

Many changes to the building regulatory system are underway in England as a result of the Grenfell Tower fire, the most significant being an effort to significantly redesign the system following recommendations put forward by the Hackitt reviews (MHCLG, 2020). Some of the many significant changes include:

- The Government will establish a new, national Building Safety Regulator, that will be responsible for:
    - implementing a more stringent regulatory regime for buildings in scope;
    - overseeing the safety and performance of all buildings; and
    - promoting the competence and organisational capability of professionals, tradespeople and building control professionals working on all buildings
- When buildings are designed, constructed or refurbished, duty-holders, including existing duty-holders identified in the Construction (Design and Management) Regulations 2015 (the Client, the Principal Designer, the Principal Contractor, designers and contractors) will have formal responsibilities for compliance with building regulations
- A new building within scope of the more stringent regime cannot be legally occupied until a Building Registration Certificate has been issued by the Building Safety Regulator. The Accountable Person, a new duty-holder for occupation, will be responsible for applying for and meeting the conditions of the Building Registration Certificate.
- Submitting a safety case report to the Building Safety Regulator will be a mandatory requirement. Mirroring the approach of most other major hazard safety case regimes, the Building Safety Manager will be required to keep the safety case up to date as a way of providing themselves, and their residents, with the assurance that they understand the fire and structural risks in their buildings and are taking

appropriate steps and actions to mitigate and manage those risks on an ongoing basis so the building can be safely occupied.

- Duty-holders will be responsible for creating and maintaining the golden thread of building information related to fire and structural safety. The golden thread will be held digitally to ensure that the original design intent and any subsequent changes to the building are captured, preserved and used to support safety improvements.
- To strengthen the oversight of the existing construction products regulatory regime, the Government will establish a new national Construction Products regulatory role, which will be responsible for:
    - Market surveillance and oversight of local enforcement action, including maintaining a national complaints system and supporting local Trading Standards in dealing with complex cases;
    - Enforcement action with manufacturers, where issues are judged to be national and/or significant; and
    - Providing advice and support to the industry to improve compliance as well as providing technical advice to the Government.
- For the new building safety system to operate effectively, it will require the competence of those working in the building sector to be of a sufficient standard to give confidence to duty-holders, regulators and residents that they are able to carry out their job in a manner that will ensure quality, safety and compliance with building regulations. This requires a more coherent and consistent approach to assessing and assuring the competence of people across all disciplines working on buildings.

It will take some time to redesign the building regulatory system in England. In the interim, some rathe significant changes have been made to the current system, including the move to restrict the use of combustible materials in the external walls of certain buildings over 18m in height (AD7, 2018). This change to AD7 has resulted in the 2018 revisions to Approved Document B – Fire Safety requiring that "building work shall be carried out so that materials which become part of an external wall, or specified attachment, of a relevant building are of European Classification A2-s1, d0 or Class A1, classified in accordance with BC EN 13501-1:2007 + A1:2009 entitled "Fire classification of construction products and building elements. Classification using test data from reaction to fire tests." (ADB, 2019b; ADB, 2019a) This provision has significant impacts for not only exterior wall systems, but for timber frame construction as well (lightweight and mass timber systems). This is a rather significant issue at the intersection of fire and 'green' building objectives. A review of potential impacts of the regulatory change can be found in Law and Butterworth (2019).

In another change, the recent update to Approved Document B – Fire Safety (ADB, 2020) regarding fire safety provisions in blocks of flats includes a reduction in the trigger height for installation of automatic sprinklers from 30m to 11m and a new recommendation for floor identification and flat indication signage within blocks of flats with storeys over 11m. This reflects the need for a more holistic approach to fire safety.

In Scotland, the regulatory system includes the Building Standards (which are equivalent to Building Regulations or Building Code in other countries), which are supported by Technical Handbooks (much like the ADs in England). Following the Grenfell Tower fire, a minor change was made to the Building Standards, amending Standard 2.4 regarding spread of fire and smoke in cavities. However, several revisions were made to the Technical Handbook: Section 2 (Fire), addressing fire performance of external cladding systems in high-rise domestic buildings and certain higher risk non-domestic buildings; provision for means of escape, evacuation alert and signage in high-rise domestic buildings (Scottish Government, 2019; Scottish Government, 2020). Specific areas addressed in changes to the Technical Handbook: Section 2 (Fire) include (Scottish Government, 2019):

- Alternative guidance throughout recognising BS 8414 (and BR 135) as an alternative full-scale façade fire test to external wall cladding/ insulation exposed in the cavity having a European Classification

A1 or A2. BS 9414 referenced to provide additional information on the application of results from BS 8414 tests

- Insulation material exposed in cavity to be European Classification A1 or A2 where storey height more than 11m
- Best practice guidance on green roofs and walls cited
- Explanation of external wall cladding expanded to include composite panels, timber panels, spandrel panels and infill panels
- External wall cladding to be European Classification A1 or A2 where storey height more than 11m
- Option for single escape stair removed for high rise domestic buildings
- Guidance on automatic smoke ventilation updated

In Australia, the performance-based regulatory approach is embodied in the National Construction Code (NCC) which provides the minimum necessary requirements for safety and health; amenity and accessibility, and sustainability in the design, construction, performance and livability of new buildings (and new building work in existing buildings) throughout Australia (ABCB, 2020). The NCC includes Volume One, which primarily applies to Class 2 to 9 (multi-residential, commercial, industrial and public) buildings and structures, and Volume Two, which primarily applies to Class 1 (residential) and 10 (non-habitable) buildings and structures. The NCC is a model code, developed by the Australian Building Codes Board (ABCB), and adopted and administered by the states and territories.

The legally enforceable component of the BCA are the Performance Requirements, which can be satisfied through: (a) a Performance Solution (Alternative Solution), (b) a Deemed-to-Satisfy (DtS) solution, or (c) a combination of the two. There are various Assessment Methods (AMs) and Verification Methods (VMs) which may be used to demonstrate compliance of different Performance Requirements.

Changes to the NCC Volume 1 2016 edition, as a result of the Lacrosse Building fire in 2014, included clarification of provisions relating to external wall claddings and attachments, to exemption from non-combustibility requirements, and to fire hazard properties of building elements. In addition, a new VM was introduced for testing the external wall assemblies for fire propagation (Hofmann and Webb, 2019), which included references to a new testing standard, AS 5113 (2016). Changes to the DtS included a requirement for sprinklers systems to be installed in apartment buildings and other residential buildings 4 stories and above, and up to 25 m in height. More recently, a Fire Safety Verification Method (FSVM) has been released as a means of verifying the fire safety of a building in order to meet the relevant Performance Requirements of NCC Volume 1 (ABCB, 2020). The FSVM provides a framework for undertaking a Performance Solution.

The regulatory system in Germany is similar to Australia, in which there is a nationally-developed model building regulation (Musterbauordnung), which is adopted and implemented at the provincial level as the applicable building regulation (Bauordnung) (Hofmann and Webb, 2019). The Musterbauordnung is function- / performance-based. In addition, there are various additional regulations and technical standards that support the system. This includes compliance with the administrative regulations (Verwaltungvorschrift MVV TB) and the Technical Building Regulations (Technische Baubestimmungen) issued by the German Institute for Building Technology (DIBt).

Concerns over fire performance of exterior walls were highlighted by a significant façade fire in Berlin in 2005, which prompted investigation into fire performance of façade systems. As a result of the investigations, various changes were made to the regulatory documents, including limits on the use of combustible material, use of bands of non-combustible materials as 'fire breaks' for horizontal and vertical fire spread where limited combustible materials are permitted, and consideration of different fire scenarios (Hofmann and Webb, 2019).

One observation that can be made from the numerous regulatory responses to the various exterior fire events is that sustainability and fire safety objectives were inadvertently placed in conflict within numerous building regulatory systems. Contributing factors are presumed to be the development of building regulations in silos, high expectations for compliance by persons that may lack appropriate qualifications and competencies, and inadequate checks that 'as built' was 'as designed' (Meacham and Strömgren, 2019; van Hees et al., 2020).

8.3.1.3 Guidance

As noted in Section 4.2 of this report, there has been considerable research conducted regarding fire performance of external wall and façade systems in recent years. Some of these works include guidance on testing, material selection, and other items which may be helpful in assessing fire performance. In addition, numerous companies, industry associations and other have provided guidance, often focused on specific products and materials. There has been guidance issued by governments (MBIE, 2019), engineering societies (e.g., SFS (2019)), and fire safety organizations (e.g. NFPA (2018a)).

As also reflected in Section 4.7 of this report, the External Façade Fire Evaluation and Comparison Tool (EFFECT) from NFPA may be of particular value in assessing whether an existing building façade system warrants attention from a fire safety perspective (NFPA, 2018a). The tool, designed for high rise buildings comprising residential or business occupancies or a mix of both and having steel or concrete structural frames, provides a range of possible mitigation measures to help begin reducing the fire risk where deemed appropriate. (The tool is not applicable to timber frame buildings and is not designed to address all possible combinations of façade system and building characteristics.)

8.3.2 Green / Vegetative Wall and Roof Systems

To provide a comprehensive picture of codes and standards associated with the design of green / vegetative (living) roofs, façades and walls, the Council on Tall Buildings in the Urban Habitat (CTBUH) undertook a research effort, *Green Living Technologies: What is Missing in the Standards?*, to identify the quality and effectiveness of the current requirements and suggestions for green living technologies and systems (Giacomello and Trabucco, 2017).

One of the major research themes was fire risk / safety. In this area, the following questions were asked:

- Are green living technologies a fire hazard?
- Which documents provide information on designing green systems for fire resistance and fire safety?
- Are the guidelines, requirements, and standards outlined in these documents enough to ensure adequate fire safety?

At this time of this research, it was observed that no standards had been developed for green façades/walls, likely due to a variety of reasons: compared to green roofs, green façades/walls are a more rare and recent design feature; there is a broad range of different types of vertical green systems (i.e., climbing plants, hydroponic walls, vertical green wall panels, etc.), making it much more difficult to create a standard that provides information for all aspects of each system; new types of systems are still being studied, tested, designed, and produced (Giacomello and Trabucco, 2017). As such, the work focused largely on green roof systems, for which a number of guidelines, requirements, and standards that included fire components were identified.

8.3.2.1 Standards

Few mandatory standards on fire protection of green roof systems were identified. However, several guidance documents are available, as listed in the next section below. Regarding mandatory standards, ANSI/SPRI VF-1 (2017), *External Fire Design Standard for Vegetative Roofs*, provides a method for designing external fire spread resistance for vegetative roofing systems. It is intended to provide a minimum design and installation reference for those individuals who design, specify, and install Vegetative Roofing Systems. FM 4477 (2010) takes an all-hazards approach, referencing various FM documents and others. With respect to fire protection, a focus is on combustibility from above and below the roof deck.

- ANSI/SPRI VF-1 (2017). *External Fire Design Standard for Vegetative Roofs*, Single Ply Roofing Industry, Waltham, MA (ANSI/SPRI, 2017)
- FM 4477 (2010). *Approval Standard for Vegetative Roof Systems*, Class Number 4477. FM Global. Norwood, MA.

8.3.2.2 Codes / Regulations

While many regulatory systems permit green walls and roofs by virtual of flexibility due to the system being functional- (as in England) or performance-based (as in Australia), no specific provisions in the regulations were identified in this search. As noted above, however, there are numerous guidance documents, as reflected in the section below. In the USA, the IBC and the IGCC have provisions related to vegetative roofs, but not specifically walls.

- IBC (2015). *Section 1507.16 Vegetative Roofs, Roof Gardens and Landscaped Roofs*, International Building Code, International Code Council, Washington, DC.
- IGCC (2015). *Section 408.3.2.4 Vegetative Roofs,* International Green Construction Code, International Code Council, Washington, DC.

8.3.2.3 Guidance

There are numerous guidance documents, reports and similar related to green roofs, in particular. The report *Fire Performance of Green Roofs and Walls* (GOV.UK, 2013) describes and classifies different types of green roofs/walls and discusses the fact that green roofs/walls are generally resistant to ignition, but recognizes that they could ignite since there has been minimal fire tests on green roofs (and none for green walls) at the time of the research. The report overviews what it considers primary measures used for fire prevention on green roofs (which can also be valid for green façades) such as increasing the non-combustible content, decreasing the amount of organic content, preventing the system from drying out and adding fire breaks for extensive green roofs.

The ASTM E2777–14 (2020) guide provides general information to practitioners in the fields of vegetative (green) roof design and construction, encouraging innovative but responsible design with a focus on performance and quality assurance. Reference is made to fire issues, and various ASTM fire test standards are cited. The FM Data Sheet 1-35 (2020) does not specific fire guidance. However, it does speak to using fire resistant plantings, maintaining fire protection separation under the vegetation (protection board), and includes reference to FM DS 9-19 (2020) on protection against wildland type fires. Many of the other guidelines are broad ranging, providing some references to regulatory requirements, standards and general concerns regarding fire. These include the German FLL (2018) *Guidelines for the Planning, Construction and Maintenance of Green Roofing*, Australian DEPI (2014), *Growing Green Guide: A guide to green roofs, walls and Façades in Melbourne and Victoria*, and *Toronto Green Roof Construction Standard, Supplementary Guidelines* from Canada, among others listed below.

Guidance Documents:

- ASTM E2777–14 (2020). *Standard Guide for Vegetative (Green) Roof Systems*, Section 5.3.9, ASTM, West Conshohocken.
- CIBSE KS 11 (2007). Knowledge Series 11, Green Roofs, Section 3 Design Considerations for Green Roofs, Chartered Institution of Building Services Engineers, London, UK, 38 pages.
- CIBSE (2013). Guidelines for the Design and Application of Green Roof System, Section 6.3 Fire Precautions, Chartered Institution of Building Services Engineers, London, UK, 108 pages.
- DCLG (2013). *Fire Performance of Green Roofs and Walls* , Report prepared by Exova Warrington Fire for the Ministry of Communities and Local Government, London, UK (GOV.UK, 2013)
- DEPI (2014). *Growing Green Guide: A guide to green roofs, walls and Façades in Melbourne and Victoria*, Dept. of Environment and Primary Industry, Victoria, Australia (DEPI, 2014)
- FLL (2018). *Guidelines for the Planning, Construction and Maintenance of Green Roofin*g, Section 8.9 Fire Prevention Measures, Forschungsgesellschaft Landschaftsentwicklung Landschaftsbau e.V. (Landscape Development and Landscaping Research Society e.V.), Bonn, Germany
- FM DS 1-35 (2020). Vegetative Roof Systems. FM Global Property Loss Prevention Data Sheet, FM Global, Norwood, MA.
- FM DS 9-19 (2020). Wildland Fire. FM Global Property Loss Prevention Data Sheet, FM Global, Norwood, MA.
- GRHC (2011). Advanced Green Roof Maintenance, Green Roofs for Healthy Cities, Toronto, ON, Canada.
- GRO (2011). GRO Green Roofs Code, Section 3.5 – Fire, Groundwork Sheffield, Sheffield, UK (GRO, 2011)
- TGRCS (undated). *Toronto Green Roof Construction Standard, Supplementary Guidelines*, Section 3.1., Office of the Chief Building Official, Toronto Building, City of Toronto, ON, Canada (TGRCS, 2017)

8.4 Lightweight Timber Construction

Lightweight timber construction has been used for many decades and is not new in the sense of some of the other systems and materials highlighted in this report. However, it is included because of the consideration of timber as a sustainable construction material, studies on the fire performance of some engineered lightweight timber systems in comparison to 'traditional' sawn timber construction, and regulatory changes that permit increased height and area of lightweight timber frame structures.

While it is agreed that, when adequately fire protected, lightweight timber can be a fire-safe and sustainable construction material, concerns exist relative to the fire performance of unprotected lightweight timber and lightweight engineered timber systems. As reported in 2012 (Meacham et al., 2012), research conducted at Underwriters Laboratories, Inc. (UL) illustrated how the evolution of lightweight timber components and connection could fail much more quickly in a fire than 'traditional' sawn timber systems (Izydorek et al., 2008; Kerber et al., 2012a; Kerber et al., 2012b). Similar testing was conducted by the National Research Council of Canada (NRCC) which looked at fire performance of home with a fire source in the basement and unprotected floor framing . Follow on research illustrated just how dangerous this can be for responding fire service personnel (Madrzykowski and Weinschenk, 2018).

As a result of research such as this, the International Residential Code (IRC), which governs one- and two-family domestic dwellings in the USA, was modified in the 2012 (IRC, 2012) edition to require a thermal barrier between the basement and the underside of floor framing members (with some exceptions, such as if automatic fire sprinklers are installed).

More recently, research in Canada (e.g., Su et al. (2008); Su and Lougheed (2014)), which points to the acceptable fire performance of adequately protected lightweight timber construction, has led to regulatory changes that permit buildings of taller heights and larger areas to be constructed with lightweight timber framing (e.g., for Canada, see extensive list of papers and reports at the website of the Canadian Wood Council (CWC) - https://cwc.ca/how-to-build-with-wood/building-systems/mid-rise-buildings-research/, or on the NRCC publications website, https://nrc-publications.canada.ca/eng/search/, accessed May 2020). This is on par with other materials (e.g., lightweight cold formed steel frame construction).

However, in recent years, there has also been a number of 'spectacular' fires which have occurred in lightweight timber frame buildings during construction, when fire protection is not yet in place (see for example Verzoni (2017)). Although fire during construction is not unique to timber framed structures, the hazards and potential risks may be higher, since the structural system itself is combustible. There are several standards and guidelines available for maintaining fire safety during construction, as overviewed below, which are critical to help manage the risk.

8.4.1 Standards

Unlike other sections, since most standards associated with fire performance of timber structural systems are the same as for other materials (e.g., concrete, steel), these are not discussed in detail here, as they are not particular to 'green' construction. The reader is encouraged to consult fire test standards promulgated by organizations such as ASTM, CEN, NFPA, ISO and others for details. Explanatory information can also found via industry organizations, such as the American Wood Council (AWC, 2020a).

In addition to fire test standards, it is important to note that standards regarding fire safety during construction are relevant, due to the fire risk that does exist with lightweight timber frame structure at this point in their lifecycles. This is highlighted since there have been a number of fires in lightweight timber framed buildings in recent years (e.g., Dunton (2014); Marrs (2015); Knapschaefer (2017); Vera (2020)), which have led to questions about the fire performance of such construction. Generally, however, it is accepted that once completed, and all fire protection measures are in place, timber-framed buildings comply with regulatory fire performance requirements.

Fortunately, standards are available for construction fire safety. An example is NFPA 241, which provides measures for preventing or minimizing fire damage to structures, including those in underground locations, during construction, alteration, or demolition (NFPA, 2019b). Among other requirements, a fire safety program, which addresses the following, is required:

(1) Good housekeeping
(2) On-site security
(3) Fire Protection systems, as follows:
    (a) For construction operations, installation of new fire protection systems as construction progresses
    (b) For demolition operations, preservation of existing fire protection systems during demolition
(4) Organization and training of an on-sire fire brigade, where applicable
(5) Development of a pre-fire plan for the local fire department
(6) Rapid communication
(7) Consideration of special hazards resulting from previous occupancies
(8) Protection of existing structures and equipment from exposure fires resulting from construction, alteration and demolition operations

Requirements and guidance related to construction fire safety, in general, and as related to timber frame buildings, exist as well, as illustrated in the following sections.

8.4.2 Codes / Regulations

As with the section 8.4.1 above, regulatory requirements for lightweight timber structural systems – in general – are largely the same as for other materials (e.g., concrete, steel), so regulatory requirements are not discussed in detail here, as they are not particular to 'green' construction (although timber is considered a sustainable material). Within the International Building Code (IBC), requirements are established largely based on use and occupancy classification of the building, and building (construction) type. Allowable heights and areas for lightweight timber framed systems, and associated fire resistance requirements, are based on these factors. A good overview of the allowances for height and area, based on building type and fire protection features installed, can be found in the guide, *2018 Code Conforming Wood Design* (AWC, 2018).

However, over the past few years there have been regulatory changes in some countries to extend the size (e.g., allowable heights and area) of structures that can be constructed with lightweight timber systems (e.g., Canada), whereas in others the use of combustible material in exterior wall systems, which can include timber framing, has been prohibited by regulation (England).

In the Canadian province of British Columbia (BC), the Building Code requirements were modified in 2009 to increase the maximum height for wood-frame residential construction from four to six stories. In part this was a result of fire research and testing in noted above (see extensive list of papers and reports at the website of the Canadian Wood Council (CWC), https://cwc.ca/how-to-build-with-wood/building-systems/mid-rise-buildings-research/, and on the NRC publications website, https://nrc-publications.canada.ca/eng/search/, each accessed last in May 2020). In addition, several studies were conducted to help frame the issues and opportunities, including a scoping study (Skulsky, 2008), a historical review of the regulatory basis for height and area requirements in the Code (Calder and Senez, 2008) and an assessment of technical and process risks associated with allowing a height increase to six stories for residential buildings (Harmsworth et al., 2008). A full list of studies can be found on the BC website (https://www2.gov.bc.ca/gov/content/industry/construction-industry/building-codes-standards/forms-resources/historical-reports, accessed June 2020). In the scoping study, one of the factors cited was that timber-framed buildings require less energy and emit less carbon when compared to other building materials, reinforcing the sustainability component (Skulsky, 2008).

In contrast to the regulatory change to allow larger buildings to be constructed of lightweight timber frame systems in Canada, concerns regarding the use of combustible material in exterior wall systems following the Grenfell Tower fir in London, England, resulted in a restriction in the ability to use timber as a structural framing material for buildings within the scope of the regulations. Buildings in scope are 18 m and higher, so the impact for lightweight timber is less than for mass timber (Section 8.5), but it is worth noting the potential impact. A review of potential impacts of the regulatory change can be found in Law and Hadden (2020).

Aside from regulatory impacts specific to timber-frame construction, requirements for fire safety during construction can be found in regulations such as the International Building Code (IBC) Chapter 33, "Safeguards During Construction" (IBC, 2018) which has provisions for fire extinguishers, standpipes, means of egress and fire watches, and the International Fire Code (IFC), Chapter 33, "Fire Safety During Construction and Demolition" (IFC, 2018) which identifies the need for such measures as:

- Precautions against fire (e.g., no smoking, fuel control)
- Provisions associated with fire watches, where required
- Access for firefighting
- Access to fire extinguishers
- Maintaining means of egress
- Availability of standpipes and adequate water supply

8.4.3 Guidance

As noted above, there are numerous nonregulatory documents available to assist in the design and regulatory compliance of lightweight timber frame construction with respect to fire performance. Some examples are listed below:

- ACW (2020). Technical Report No. 10. Calculating the Fire Resistance of Exposed Wood Members. American Wood Council. Leesburg, VA. USA (https://www.awc.org/pdf/codes-standards/publications/tr/AWC_TR10_20200520_AWCWebsite.pdf, accessed June 2020)
- ACW (2020). Design for Code Acceptance 3. Fire-Resistance-Rated Wood-Frame Wall and Floor/Ceiling Assemblies. American Wood Council. Leesburg, VA. USA (https://www.awc.org/pdf/codes-standards/publications/dca/AWC_DCA3_20200401_AWCWebsite.pdf, accessed June 2020)
- AWC and IBC (2020). Mass Timber Buildings and the IBC. American Wood Council. Leesburg, VA. USA and International Code Council, Washington, DC, USA.
- Podesto, L. (2015). Maximizing Value with Mid-Rise Construction. WoodWorks®. Wood Products Council (https://www.woodworks.org/wp-content/uploads/Maximizing-Value-with-Mid-Rise-Construction.pdf, accessed June 2020)
- STA (2020). Structural timber buildings fire safety in use guidance Volume 1 - Pattern book systems. Structural Timber Association UK.
- STA (2020a). Structural timber buildings fire safety in use guidance Volume 2 - Cavity barriers and fire stopping. Structural Timber Association UK.
- Wood Solutions website, Forest and Wood Products Australia Ltd (website with numerous reports, https://www.woodsolutions.com.au/articles/design-fire, accessed June 2020).

Also, much like NFPA 241 provides fire safety guidance for buildings under construction, guidance on construction fire safety is available in other countries (e.g., HSE (2010)). In addition, specific guidance for timber-framed buildings is available as well. Examples include the TRADA (2012) *Fire safety on timber frame construction sites* and the *Fire Safety During Construction for Five and Six Storey Wood Buildings in Ontario: A Best Practice Guide* (TRADA, 2012; MMAH, 2016). A range of best practice guides is available from the Construction Fire Safety Coalition website as well (https://constructionfiresafety.org/best-practices, accessed June 2020).

8.5 Mass Timber Construction

Mass timber construction, using large cross-sectional area timber for structural members such as columns, beams and joists, dates back centuries. So too do building regulations aimed at mitigating the fire risk associated with significant use of timber in construction. In England, for example, the "Rebuilding Act" implemented after the fire of London in 1666, established such requirements as acceptable types of houses, minimum thickness of brick walls, and heights from floor to ceiling, sufficiency of party walls for each type of house (Bell, 1920). Aspects such as the minimum thickness of brick were to address fire spread issues. Similar requirements for roof material and related building aspects were also implemented. As the British (and others) colonized new territories, such as North America, such requirements were carried along (Liebing, 1987; Platt, 1996; Wermiel, 2000). By the late 19th Century, a specific approach for the use of heavy timber construction in mills, known as 'slow-burning construction' (Woodbury (1882) and BMMFIC (1899), as cited in Wermiel (2000)), became widely used in the New England region of the US. The research, development and guidance that underpinned and advanced this approach ultimately helped facilitate the development and use of the automatic fire sprinkler, the founding of FMGlobal, Underwriters Laboratory, Inc. and the National Fire Protection Association, led to the publication of the first model building fire safety code by the National Board of Fire Underwriters, and was the start of 'fire protection engineering' (Wermiel, 2000). The concepts behind this approach are still reflected in the 'heavy timber construction' types in current building codes of the ICC and the NFPA.

More recently, however, a new generation of engineered heavy timber systems, broadly referred to as 'mass timber', is becoming widely accepted and used. As used here, mass timber systems includes glue laminated timber (glulam), cross laminated timber (CLT), nail laminated timber (NLT), dowel laminated timber (DLT), laminated veneer lumber (LVL) and laminated strand lumber (LSL), along with wood and concrete composite systems and construction. Mass timber has received much attention as it is perceived to be more sustainable than many other construction materials (Ruuska and Häkkinen, 2014; Crawford and Cadorel, 2017). The potential for using mass timber systems in larger and taller buildings, for sustainability purposes, triggered considerable research into fire performance of such systems, as discussed in Section 4.5. Of importance to this discussion is the change in standards, regulations and guidance facilitated by this extensive research. While changes have been made in several countries, the focus here is in North America.

8.5.1 Standards

In the USA, mass timber systems, like other structural materials and systems, must be tested to ASTM E119-20 (2020) or UL 263 (2014) to obtain the requisite fire resistance rating. In Canada, the equivalent would be CAN/ULC-S101 (2007). In the USA, design is carried out following the National Design Specification for Wood Construction (AWC, 2018) and the ANSI/APA PRG 320, Standard for Performance-Rated Cross-Laminated Timber (ANSI/APA, 2018). It is worth noting that due to concerns with CLT adhesive performance under elevated temperatures, from the 2021 edition onward, ANSI/APA PRG-320 will require all CLT panel systems to use adhesives that provide an increased resistance to elevated temperatures.

In Canada, the relevant design standard is CSO-86, Engineering Design in Wood (CSA, 2014). For CLT systems, the associated CLT Handbook (USA and Canadian versions) are also used (FPI, 2013; 2019). (These standards and handbook cite requirements for the fire resistance testing.) In terms of assessing fire performance, a new standard was developed, CAN/ULC S146 (2019), Standard Method of Test for the Evaluation of Encapsulation Materials and Assemblies of Materials for the Protection of Mass Timber Structural Members and Assemblies.

The approach is similar in other countries as well. For example, there is also a Swedish version of the CLT Handbook (SW, 2019). The Swedish CLT Handbook refers mainly to European construction standards and the Eurocodes. The national determined parameters (NDPs) associated with the Eurocodes for Sweden are set out in the Building Regulations (BBR) of the National Board of Building, Housing and Planning (Boverket) and its general recommendations on the application of European design standards, EKS 10 (BFS 2015:6).

- ANSI/APA PRG 320 (2018), Standard for Performance-Rated Cross-Laminated Timber, Engineered Wood Association. Tacoma. WA.
- ASTM E119-20 (2020). Standard Test Methods for Fire Tests of Building Construction and Materials. American Society for Testing and Materials. West Conshohocken, PA.
- AWC (2018). National Design Specification for Wood Construction. American Wood Council. Leesburg, VA.
- CAN/ULC-S101-14-REV1 (2014). Standard Methods of Fire Endurance Tests of Building Construction and Materials. Underwriters Laboratories of Canada, Ottawa, Ontario.
- CAN/ULC-S134 (2013). Fire Test of Exterior Wall Assemblies, Underwriters Laboratories of Canada, Ottawa, Ontario.
- CAN/ULC S146 (2019). Standard Method of Test for the Evaluation of Encapsulation Materials and Assemblies of Materials for the Protection of Mass Timber Structural Members and Assemblies.
- CSA (2014). CSA O86 - Engineering Design in Wood. Canadian Standards Association.
- UL 263 (2014). Fire Tests of Building Construction and Materials. Underwriters Laboratories Inc. Northbrook, IL.
- SW (2019). CLT Handbook. Swedish Wood (Svenskt Trä). Stockholm. Sweden.

8.5.2 Codes / Regulations

As discussed in Section 8.4 above, fire performance requirements for structural systems in the USA are established largely based on use and occupancy classification of the building, and building (construction) type. Allowable heights and areas for lightweight timber framed systems, and associated fire resistance requirements, are based on these factors (including exceptions to limits based on such factors as presence of fire sprinkler systems).

The historic 'heavy' timber construction is considered Type IV construction. In concept, it seemed appropriate to include new mass timber systems in this construction type. However, while mass timber systems have some features in common with 'heavy' timber systems, there are many more differences, both with panelized construction and concrete composite systems. As such, and informed by the extensive research as overviews in Section 4.5, it was believed that a somewhat different approach was needed. Ultimately, within the International Code Council system, which develops the International Building Code (IBC), it was decided to create new construction types for mass timber systems: Mass Timber Type IV-A, Type IV-B, and Type IV-C. In contrast to the historical approach of considering timber systems as combustible, these new construction types more closely mirror the fire resistance ratings in non-combustible Type I-A and Type I-B construction, and Types IV-A and IV-B contain additional criteria for the protection of mass timber by non-combustible materials (encapsulation).

There are several summaries of the code changes available, including Breneman et al. (2019) and O'Brocki (2019). An in depth discussion of the development of the code changes and comparison to existing construction typologies can be found in Breneman et al. (2019). A brief summary of the major changes are as follows.

Type IV-C buildings will be permitted to be constructed up to a maximum of nine stories for Group B (business) occupancies, with all other occupancies having lower limits. Exposed mass timber is permitted, except in concealed spaces, shafts, hoist ways, interior exit enclosures, and outside of exterior walls. The structure needs a 2-hour fire resistance rating throughout, and the building needs to be fully sprinklered. Lightweight timber framing is not permitted as part of the building.

Type IV-B buildings will be permitted to be constructed up to a maximum of 12 stories for most occupancy types, with some exceptions such as Mercantile and Storage. Only a limited amount of exposed interior mass timber will be permitted, with all other mass timber protected with noncombustible materials equaling 2/3 the required rating, including concealed spaces, shafts, hoist ways, and interior exit enclosures. Noncombustible protection of 40 minutes fire resistance will be required on the outside of exterior walls. The structure needs a 2-hour fire resistance rating throughout, and the building needs to be fully sprinklered. Lightweight timber framing is not permitted as part of the building.

Type IV-A buildings will be permitted to be constructed up to a maximum of 18 stories for most occupancy types, with some exceptions such as Mercantile and Storage. No exposed mass timber is permitted, and all interior mass timber must be protected with noncombustible protection equaling 2/3 of the required fire resistance rating, including concealed spaces, shafts, hoist ways, and interior exit enclosures. Noncombustible protection of 40 minutes fire resistance will be required on the outside of exterior walls. The structure needs a 2-hour fire resistance rating throughout, and the building needs to be fully sprinklered. Lightweight timber framing is not permitted as part of the building.

It is worth noting that the required fire resistance rating is as per standard fire tests ASTM E119 or UL 263, but that a performance-based option to determine the contribution to the fire resistance rating provided by noncombustible protection is provided. Guidance is available via the handbooks outlined above, industry guidelines and related sources.

The situation is somewhat similar with respect to the National Building Code of Canada (NBCC), 2020 edition, where buildings of a Group C major occupancy type (i.e., residential occupancy) would be permitted to be constructed to a maximum of 12 stories and 6,000 square meters, and buildings of a Group D major occupancy (i.e., business and personal services occupancy) could be constructed up to 12 stories and a maximum building area of 7,200 square meters (Sorensen, 2019). In the NBCC, the mass timber construction type is referred to as encapsulated mass timber construction (EMTC), and includes CLT, NLT and glulam systems. In the case of the NBCC, requirements include a minimum thickness of 96 mm of mass timber and a minimum 50-minute fire rating, which was derived from CAN/ULC S146 (2019). In brief, the floors in EMTC buildings must have a two-hour fire resistance rating, the mezzanines a one-hour rating and load-bearing walls, columns and arches, not less than the fire-resistance required for the use of the building, and an automatic fire sprinkler system is required. The Province of British Columbia has adopted these provisions into their Building Code in advance of the publication of the 2020 NBCC.

In many countries outside of North America, where functional- or performance-based building regulations are in place, there are less restrictions to the construction of tall mass timber structures. Countries such as Australia and New Zealand in the Asia-Oceania, and Austria and Sweden in Europe, permit tall mass timber buildings. As with discussion above for the USA and Canada, mass timber systems would typically be expected to comply with applicable fire test standards (e.g., CEN, ISO, etc., as discussed in the Swedish context).

Until recently, the Building Regulations in England permitted tall mass timber construction as well. However, as noted in Section 8.4, concerns regarding the use of combustible material in exterior wall systems following the Grenfell Tower fir in London, England, resulted in a restriction in the ability to use timber as a structural framing material for buildings within the scope of the regulations. This has had an impact on tall mass timber building construction going forward. In particular, restrictions apply to use of CLT in exterior walls above 18m. (Mass timber high rise buildings can still be constructed, but cannot use CLT in the exterior wall.) A review of potential impacts of this regulatory change in England can be found in Law and Butterworth (2020).

8.5.3 Guidance

In addition to standards, many countries have guidance documents on design of mass timber buildings, which include fire safety requirements (e.g., fire performance testing). In many cases, such guidance is published by the timber industry. A representative list of guidance documents for CLT systems is provided below.

- APA (2019). Engineered Wood Construction Guide. Engineered Wood Association.
- FPI (2013). CLT Handbook – US Edition. FPInnovations and Binational Softwood Lumber Council. Pointe-Claire. Quebec. Canada
- FPI (2019). CLT Handbook – Canadian Edition. FPInnovations. Pointe-Claire. Quebec. Canada
- STA (2015). Cross-laminated timber construction – an introduction. Structural Timber Engineering Bulletin 11, Structural Timber Association. (http://www.structuraltimber.co.uk/assets/InformationCentre/eb11.pdf, accessed June 2020)
- SW (2019). CLT Handbook. Swedish Wood (Svenskt Trä). Stockholm. Sweden.

8.6 Modular Construction

The terms 'modular construction' and 'permanent modular construction' (PMC) broadly refer to the process by which components of a building are prefabricated off-site in a controlled setting and then shipped to the project site and assembled (MBI, 2019a; Wilson, 2019). For 'fully assembled' modules, the term prefabricated prefinished volumetric construction (PPVC) is used as well (BCA, 2020). Benefits include the ability to capture the efficiencies gained by integrating the processes and technologies of design, manufacturing, and construction, without having to compromise on aesthetic intent, resulting in higher-quality buildings, delivered in a shorter time frames, with more predictable costs, and fewer environmental impacts. including through reduced material use and waste (Wilson, 2019). Such buildings can be constructed of wood, steel, or concrete. Industry assessments reflect an increased use of modular construction over the past 3 years, and project even higher use in the coming 3 years (Buckley et al., 2020). A significant driver is cost savings (Bertram et al., 2019; Buckley et al., 2020), with estimates of 20% in construction cost savings over traditional methods, and a potential market value on $130 Billion in Europe and the USA by 2030 (Bertram et al., 2019).

8.6.1 Standards

In North America, there is no specific 'modular building code' for modular construction; rather, such buildings and components are subject to state / province and local building codes (MBI, 2020). As such, components and systems are subject to the same fire performance test standards as 'traditional' construction materials and systems.

8.6.2 Codes / Regulations

As noted above, there is no specific 'modular building code' for modular construction in North America; rather, such buildings and components are subject to state / province and local building codes (MBI, 2020). As such, they comply with the International Building Code (IBC) in the United States and the National Building Code (NBC) in Canada, as adopted into law at the state / province and local level.

In Singapore, however, there are requirements associated with 'buildability' of PPCV buildings (BCA, 2017), and various guidance exists (e.g., BCA, undated). A significant reason for this is that as of 2014, Singapore requires that certain types of buildings be constructed of PPVC (see BCA website, https://www1.bca.gov.sg/buildsg/productivity/design-for-manufacturing-and-assembly-dfma/prefabricated-prefinished-volumetric-construction-ppvc, accessed June 2020).

8.6.3 Guidance

There are various guidance documents related to modular construction available in the USA (e.g., AIA, undated) and elsewhere (e.g., BCA (2000); BCA (2020); BCA (undated)). Guidance ranges from considerations for design to buildability (constructability), and sometimes includes quality control. In general it is expected that fire performance requirements, as mandated in codes and regulations, be met, so fire is not addressed as a specific consideration in most guidance. However, the PPVC Guidelines (BCA, undated) have a section (3.4) on fire safety requirements, which points to compliance with the Building Code for fire resistance and fire performance of materials.

Regarding a rather different type of modular construction, the use of shipping containers as buildings or building components, guidance has been developed on how to adopt such containers for building use (e.g., see ICC G5 (2019)). While perhaps not considered 'green' construction by some, the repurposing of the containers fits the recycling component of sustainability well.

8.7 Sustainability and Resiliency Goals in Building Regulations

Research has found that challenges exist in incorporating sustainability and resiliency objectives into building regulations for both new and existing buildings. Analysis of building code formulation in nine building codes within and outside the Asia-Pacific region was undertaken to explore the extent to which sustainability and resiliency were addressed (UN ESCAP, 2012). In this work, four reference countries were selected – USA

(California), Singapore, Australia and the United Kingdom – along with five target countries in the Asia-Pacific region – Thailand, India, Bangladesh, the Philippines and Sri Lanka. All building codes were analyzed for six elements of environmental sustainability (material conservation, energy conservation, water conservation, soil/land conservation, solid waste reduction and air pollution control) and six elements of disaster resilience (wind loads, snow loads, seismic effects, rain/flood resistance, wildfire and landslide resistance).

With regards to environmental sustainability, the ESCAP report found that this is a relatively new element in Asian building codes and is therefore not well integrated. Of the five target countries, India was the only country that addressed all six elements of environmental sustainability. However, most of the building code is voluntary, and the parts that are mandatory have low compliance levels. The main conclusion regarding disaster resilience is that some hazards have been addressed reasonably well (e.g., storms and typhoons in all codes) and others not, and that a variety of approaches were employed to encourage better disaster resilience (e.g., fiscal incentives (Japan), financial incentives (India), zoning incentives (Republic of Korea) and a combination of all (Singapore). In the end, the analysis suggested that it is possible to improve environmental sustainability and disaster resilience of the built environment even in least developed countries, with the main challenge being to find incentives that work in a specific context considering financing, human capacity, enforcement capacity and stakeholder cooperation.

Research in 2016 found that similar challenges exist in incorporating sustainability and resiliency into building regulation in high-income countries (Meacham, 2016). Similar to outcomes from the ESCAP study, it was found that although the considered countries included some sustainability and resiliency objectives, these societal objectives were not yet being viewed as having the same level of importance, or equivalent level of social compact between government and the public, as providing for minimum levels of health and safety in buildings. Furthermore, the holistic or integrated performance obtained through application of the regulations and guidance has not yet been fully assessed (i.e., making sure that adding a new objective does not result in an unanticipated impact somewhere else), creating a potential for unintended consequences. Unfortunately, the lack of holistically reflecting the desired performance of buildings from a sustainable and fire resilient perspective was observed with the 2017 Grenfell Tower fire in London (MHCLG, 2017a; MHCLG, 2018b; MHCLG, 2018a; Meacham and Strömgren, 2019; van Hees et al., 2020).

Focusing on the challenges with resiliency objectives, the report from a 2012 workshop organized by the U.S. Department of Homeland Security on community resiliency identified a role for codes and standards in disaster resiliency, but found that gaps exist and changes are needed (US DHS, 2010).

"Traditionally, building codes have regulated life safety issues. New building codes and standards should extend beyond life-safety aspects to include resilient design concepts in a performance-based approach as well as continuity of operations. They should rely on common and widely adopted methods of measurement, provide a flexible framework to address different facility types, address types of structures (from residential to large commercial and industrial structures), and recognize the differing levels of performance that are required. Uniform adoption of resiliency objectives by jurisdictions requires including resiliency requirements in the current model building codes, educating regulators and their constituents, and incentivizing the application, inspection, and regulation of resiliency approaches. This process begins with the development of criteria, codes, and standards that address resiliency objectives and the supporting tools and validation for their use."

As a means to further facilitate adoption of resiliency into building codes as standards, the U.S. National Institute for Standards and Technology (NIST) identified research needed to facilitate development of guidelines and standards for disaster resilience of the built environment (McAllister, 2013). As with the DHS report noted above, it was identified that performance goals and resilience metrics are needed for all building systems. It was suggested that one starting point would be to identify such goals and metrics in current building codes and standards.

This topic was explored in a 2014 project by the Fire Protection Research Foundation that identifies how disaster resiliency is, and could be, addressed within NFPA codes and standards (Dungan, 2014). The report notes that "applying many of the concepts of resiliency to fire related incidents would introduce some new language but would not radically change the fire safety requirements. It could, however, require more explicit definitions of performance objectives."

This finding is in line with outcomes from a 2010 DHS workshop report noted above and the 2016 assessment (Meacham, 2016), which found that overall:

- Mechanisms are needed to define and quantify better levels of tolerable building performance, be they in terms of health, safety, welfare, risk, sustainability or other measures.
- Quantified performance metrics must be developed and incorporated into regulations. Recognizing that some metrics may be best addressed prescriptively (e.g., rise and run of a stair), there remains significant scope for performance measures, for which associated verification methods are needed.
- Tools and methods for helping with the enforcement of performance-based building regulations are still lacking. In part related to the lack of quantified performance measures, those responsible for approval of designs and enforcement of regulations are faced with the challenge of making decisions in the face of significant uncertainty.

Moving forward, concepts of sustainability and fire resilient (SAFR) buildings needs to be integrated into building regulatory development (see Chapter 7).

8.8 'Green', Sustainable, Energy Regulations

Over the past few decades, there has been increasing focus on energy conservation, sustainable development and sustainable construction. This triggered development of a wide range of regulations, codes, standards and guidelines for energy and sustainability performance of buildings, as well as the non-regulatory assessment and certification mechanisms such as LEED, BREEAM, and others. A good overview of various regulations, standards, and rating schemes is presented by Vierra (2019) and is not detailed here. However, a few examples are explored from the perspective of if and how fire safety is addressed, in particular regarding 'green' or energy regulations.

As a general observation, 'green, sustainable and energy' regulations applied most new construction will require compliance with the building and fire regulations with respect to fire safety provisions. However, the situation is not so clear for alterations, renovations and upgrades to existing buildings. Building regulations (codes) vary in terms of when building permits are required, and the extent to which compliance with current regulations is needed, often based on the extent to which repair, renovation or upgrade is planned. This is generally a local decision (in the USA), and therefore beyond the scope of this review to explore in detail. However, as an example of work for which a permit is not required, the City of Portland, OR, pamphlet on when a permit is required is illustrative (City of Portland, 2020). This list includes:

- Install insulation in existing homes
- Replace doors or windows if the existing openings are not widened or reduced in size

As discussed in Chapter 4 of this report, there are types of insulation material which are combustible, and some window framing with PVC or other synthetic materials have been shown to fail more quickly in a fire than wood or other framing systems. As such, there is the potential for energy retrofits to result in potential fire hazards and risks, with no permitting and therefore no particular government oversight. This is a challenge that has also been recognized for energy performance rating schemes (e.g., Meacham et al. (2012)), such as LEED, which are extra-regulatory, with the assumption that building fire safety measures are addressed elsewhere (i.e., by the regulations). The result is a particular challenge for energy upgrades to existing buildings.

This challenge is not limited to the US, or to small, single-family dwellings. As noted in Chapters 3 and 4, as well as earlier in this Chapter, arguably the energy retrofit of the Grenfell Tower, and lack of identification and treatment of the use of combustible insulation, was a factor in the magnitude of the resulting fire (e.g., see MHCLG (2017a); MHCLG (2018b); MHCLG (2018a); Meacham and Strömgren (2019); van Hees et al. (2020)). The potential was also identified in energy retrofits in Spain (Sánchez-Ostiz et al., 2014a), where it was identified that application of combustible insulation could result in unintended fire safety consequences. Overall, it is with modification to existing building where the highest risk potential exists specifically associated with energy retrofits.

8.8.1 ICC Green Construction Code

The International Green Building Construction Code (IgCC) is the first model code in the USA to include sustainable measures for the entire construction project and its site. The primary focus is new buildings, but it is also applicable to existing buildings, with some exemptions. The intent of the code is to make buildings more efficient, reduce waste, and have a positive impact on health and community welfare (ICC, 2018c). The IgCC may be adopted by jurisdictions and it becomes mandatory for all applicable projects. A jurisdiction, however, may adopt the code as a voluntary set of guidelines. The code can be customized by jurisdiction by incorporating certain requirements that are appropriate for the local area. The technical content of the IgCC focuses on six topics:

- Site Development and Land Use
- Material Resource Conservation and Efficiency
- Energy Conservation, Efficiency and CO_2 Emission Reduction
- Water Resource Conservation, Quality and Efficiency
- Indoor Environmental Quality and Comfort
- Commissioning, Operation and Maintenance

Section 102.4 of the IgCC (2018) notes that the International Building Code (IBC, 2018) and the International Fire code (IFC, 2018) shall be considered part of the code. So, while there are 'green' features in the IgCC, such as thermal insulation requirements, minimization of material usage, and requirements for alternative energy sources, they must comply with the fire safety requirements within the IBC and IFC as discussed earlier in this report. This helps to reduce the potential for unintended consequences related to fire performance of 'green' materials, systems and features.

One area of potential concern, which is not specific to the IgCC, is with respect to existing buildings. While it is made clear in the IgCC that compliance with applicable provisions of the IBC and IFC is required, depending on the scale of repair, renovation, retrofit or upgrade to an existing buildings, not all provisions may be required. This could in some cases result in energy retrofits presenting an unintended fire consequence, in particular if parties involved in the building modification are unaware of the potential impacts.

8.8.2 California Green Building Standards Code

The California Green Building Standards Code (CALGreen) (CBSC, 2019) aims to improve public health, safety and general welfare by enhancing the design and construction of buildings through the use of building concepts that have a reduced negative impact on the environment, or a positive impact on the environment, and which encourage the use of sustainable construction practices. This is accomplished through a focus on:

- Planning and design
- Energy Efficiency
- Water efficiency and conservation
- Material conservation and resource efficiency
- Environmental quality

With respect to fire safety, the CALGreen requires compliance with the fire safety provisions as embodied within CCR Title 19 Division 1 (CCR, 2014) and CCR Title 24 Parts 2 (CCR, 2019a) and 9 (CCR, 2019b). CCR Title 24 Part 2 is based on the 2018 IBC, and CCR Title 24 Part 9 is based on the 2018 IFC.

As with the IgCC discussion above, the level of compliance with fire safety provisions in existing buildings (as compared to new construction) varies depending upon extent of changes to the building. As such, it is possible that energy performance (or related sustainability) upgrades could result in the potential for unintended fire consequences in some cases.

8.8.3 International Energy Conservation Code

The International Energy Conservation Code (ICC, 2018b), a model code developed by the International Code Council (ICC) in the USA, regulates minimum energy conservation requirements for new buildings and certain existing buildings. The IECC addresses energy conservation requirements for all aspects of energy uses in both commercial and low-rise residential construction (3 stories or less in height above grade), including heating and ventilating, lighting, water heating, and power usage for appliances and building systems.

As with the IgCC overviewed above, the IECC is not meant to override any safety requirements mandated by other regulations, and all materials and systems need to comply with the requirements of the IBC. This provides some nominal level of fire performance requirements for insulation, window casings, and other materials that might be installed based on the requirements of the IECC.

Areas in which potential fire performance issues might arise are in association with requirements for insulation and sealing of cavities for thermal performance.

8.8.4 Energy Performance of Buildings Regulation

To increase the energy performance of buildings, the European Union (EU) established a legislative framework that included the Energy Performance of Buildings Directive 2010/31/EU (EPBD) and the Energy Efficiency Directive 2012/27/EU (EC, 2020). Both directives were amended, as part of the Clean energy for all Europeans package in 2018 and 2019, with the Energy Performance of Buildings Directive (2018/844/EU). EU countries need to transpose the new and revised rules into national law by 10 March 2020.

Among the several issues addressed in the EPBD, EU countries must set cost-optimal minimum energy performance requirements for new buildings, for existing buildings undergoing major renovation, and for the replacement or retrofit of building elements like heating and cooling systems, roofs and walls, and the health and well-being of building must addressed through the consideration of air quality and ventilation.

As with the other regulations outlined above, compliance with the EPBD assumes compliance with the building regulations of member states, which include fire performance requirements. In this regard, ideally there are no particular issues arising from the implementation of EPBD requirements. However, like with the other regulations, retrofit of existing buildings can create opportunities for introduction of combustible insulation, potential sources of ignition through photovoltaic system installations, and other concerns outlined in this report in cases where the level of compliance checking and/or regulatory oversight is at a different level for existing buildings than for new buildings.

8.8.5 Passivhaus (Passive House) Standard

The passive design strategy for buildings models and balances a comprehensive set of factors, including heat emissions from appliances and occupants, to keep a building at comfortable and consistent indoor temperatures throughout the heating and cooling seasons. It is based on a set of five design principles (PHIUS, 2020):

- The building envelope is extremely airtight, preventing infiltration of outside air and loss of conditioned air.
- Employs high-performance windows (double or triple-paned windows depending on climate and building type) and doors - solar gain is managed to exploit the sun's energy for heating purposes in the heating season and to minimize overheating during the cooling season.
- Uses some form of balanced heat- and moisture-recovery ventilation.
- Uses a minimal space conditioning system.

The foundational design principles of greater insulation, airtight building envelopes, high-performance windows, energy recovery ventilation and managing solar gain originated in the United States and Canada in the 1970s, but were advanced in Europe and gained broad attention with the formation of the Passivhaus Institut (Passive House Institute) in Germany in 1996 (PHI, 2020). Criteria for reflecting achievement with the passive targets vary by region due to climatic conditions, which is why the standards are slightly different in the US and Europe, for example. Certification of compliance with the PHIUS Passive Building Standard is available (e.g., PHIUS (2019); PHIUS (2020)), much like LEED or other 'green' building certification. Details about passive design principles can be found in Wright and Klingenberg (2015).

From a fire safety perspective, the main issues of potential concern are the possible use of combustible insulation, overpressures and unsafe conditions that can result during a fire, and the lack of mechanical ventilation, which if present may have some benefit for smoke control (particularly in commercial buildings). These are similar to concerns with other 'green' rating schemes. However, like the other schemes, regulations and guidelines, new construction is expected to meet local building and fire requirements, and retrofit of existing buildings creates the bigger concern.

9. Firefighting Tactics

Fire risks and hazards of 'green' building materials, systems (technologies) and features can pose significant challenges for the fire service. This was noted in the 2012 report (Meacham et al., 2012), which cited work by the National Association of State Fire Marshals (Tidwell and Murphy, 2010), Underwriters Laboratories Inc. (e.g., Backstrom and Dini (2011); Kerber et al. (2012b)), the FPRF (e.g. Grant (2013)) and others that had highlighted concerns for the fire service.

Since the 2012 report was published, the number of research efforts, training programs and resources for the fire service related to fire safety challenges of 'green' building materials, systems (technologies) and features have grown. A few of the many resources are noted here.

Fire Protection Research Foundation (FPRF)

The FPRF has assembled research reports, workshop reports, training information and similar resources for the fire service which are available through a single weblink (https://www.nfpa.org/News-and-Research/Data-research-and-tools/Emergency-Responders, accessed August 2020). While not all resources are directly associated with fire safety challenges of 'green' building materials, systems (technologies) and features, many are. The following is a list of titles of resources available from this site that are pertinent to this topic:

Fireground Tactics

- Flammable refrigerants firefighter training: Hazard assessment and demonstrative testing (2019)
- Development of Fire Mitigations Solutions for PV Systems Installed on Building Roofs - Phase 1 (2016)
- Research Roadmap for Smart Fire Fighting (2015)
- Development of Emergency Responder SOPs/SOGs: Using Crowdsourcing to Address Electric Vehicle Fires (2014)
- Best Practices for Emergency Response to Incidents Involving Electric Vehicles Battery Hazards: A Report on Full-Scale Testing Results (2013)

Electric/Alternative Fuel Vehicles

- Alternative Fuel Vehicle Responder Training (2017)
- Best Practices for Emergency Response to Incidents Involving Electric Vehicles Battery Hazards: A Report on Full-Scale Testing Results (2013)

UL Firefighter Safety Research Institute (UL FSRI)

The UL FSRI is dedicated to increasing firefighter knowledge to reduce injuries and deaths in the fire service and in the communities they serve (https://ulfirefightersafety.org/, accessed August 2020). It investigates residential, commercial, and industrial fires through full-scale testing, field-testing, and modeling to replicate actual fires faced by firefighters. Research results are shared through interactive training courses that have reached hundreds of thousands of firefighters globally.

A list of UL FSRI research projects is available here (https://ulfirefightersafety.org/research-projects/index.html, accessed August 2020). Some of the projects related to fire safety challenges of 'green' building materials, systems (technologies) and features include:

- Study of Firefighter Line of Duty Injuries and Near Misses (e.g., including a recent report on the 2019 ESS explosion in Arizona)

- Firefighter Safety and Photovoltaic Systems
- Impact of Ventilation on Fire Behavior in Legacy and Contemporary Residential Construction
- Structural Stability of Engineered Lumber in Fire Conditions
- Improving Fire Safety by Understanding the Fire Performance of Engineered Floor Systems

A list of UL FSRI training courses is available here (https://training.ulfirefightersafety.org/, accessed August 2020). As specifically related to fire safety challenges of 'green' building materials, systems (technologies) and features, the training site does not currently list any. However, it is noted that there was a training on Firefighter Safety and Photovoltaic Systems, which is currently showing as under redevelopment. Readers are urged to check the site regularly as new programs will be available when ready. It is also noted that some topics relevant to fire safety challenges of 'green' building materials, systems (technologies) and features may be covered in various modules not specified as such.

A comprehensive set of UL FSRI resources is available here (https://ulfirefightersafety.org/resources.html, accessed August 2020). This includes the complete collection of reports, videos, and online training.

Published Reports

In addition to resources such as the FPRF and UL FSRI noted above, various entities have conducted research into firefighting tactics associated with fire safety challenges of 'green' building materials, systems (technologies) and features. A few representative reports are highlighted here.

Photovoltaics and Firefighters' Operations: Best Practices in Selected Countries (Namikawa et al., 2017).
This report reviews guidelines related to firefighter safety from Japan, the United States, and Germany with respect to PVS. Approaches to mitigate hazards to firefighters are identified according to the following:

1. Identify structures with PV systems installed.
2. Minimize potential hazards in firefighter operations (e.g., ensure sufficient working space and mitigate electrical shock hazards).
3. Prevent/contain fires originating from the PV system.

To implement the approaches associated with the above, the following categories have been identified:

1. Installation requirements that consider firefighter operations (PV installation)
2. Operational strategies for firefighters when PV is present (firefighter operations)
3. Implementing technologies to minimize potential hazards from PV systems (technology implementations).

Table 9.1 summarizes best practices to reduce potential hazards for firefighters as analyzed from guidelines based on the above framework.

Table 9.1 Summary of Best Practices to Reduce Potential Hazards for Firefighters (Namikawa et al., 2017)

Approach	Purpose	Categories	Best Practices
Identify structures with PV systems installed	Alert firefighters to the presence of PV systems	PV installation	- Mark (label) on distribution boxes or other standard location
Minimize potential hazards in firefighter operations	Ensure sufficient access and working space	PV installation	- Walkways with a certain width - Setbacks from roof boundaries
	Mitigate electrical shock hazard from PV systems	PV installation	- Label on DC cables - Map of DC cable layout affixed to distribution boards, etc. - DC cable laying outside installation / DC cable with grounded metallic conduit
		Firefighters' operations	- PV system de-energizing procedure (outside the array boundary) - Maintain 'approach boundary' of PV systems when energized - De-energize the array
		Technology implementations	- Rapid shutdown (firefighters' switch) outside the array boundary
	Mitigate electrical shock hazard from hose water streams	Firefighters' operations	- Maintain minimum distance with hose streams
	Minimize exposure to hazardous chemicals from PV modules that are on fire		- Personal protective equipment including Self-contained breathing apparatus
Prevent fires originating from the PV system	Interrupt DC fault to prevent sustained arcs and ground faults	Technology implementations	- Ground-fault circuit interrupter - Arc-fault circuit interrupter

The analysis in this report reveals the value in preparing guidelines in collaboration with those involved in developing the PV industry (technologists, installers, electricians, and inspectors) and firefighter organizations and disseminating the guidelines through the respective channels

<u>Rooftop PV Systems and Firefighter Safety (DNV GL, 2015)</u>
This report summarizes findings from a DNV GL study of firefighter rooftop operations, the hazards they may encounter when working around PV arrays, and means in which electrical hazards in particular can be mitigated or substantially reduced. The study included three major tasks: 1) a review of relevant publications focused on firefighting issues specific to PV, including tests performed in the U.S. and Germany; 2) in-depth interviews with firefighters discussing their rooftop operations, concerns and decision making processes with respect to PV; and 3) a Failure Mode and Effects Analysis (FMEA) based evaluation of various methods of shock-hazard reduction. Some of the findings include (DNV GL, 2015):

- Recently revised building codes mandating enhanced access around rooftop PV arrays represent a significant improvement and give firefighters more opportunity to carry out vital rooftop operations. However, their physical presence can still impede specific operations and will continue to impact the tactical decision-making process of firefighters at the scene of a building fire.
- UL testing has demonstrated effective methods of safely fighting fires involving PV arrays. It also demonstrates that there are currently no practical means of entirely eliminating shock hazard in arrays, particularly given uncertainties of failure or damage to components not typically used for safety measures.

- A joint PV and fire industry study conducted in Germany recommended against requiring module level electronics because of reliability concerns and the potential to create a false sense of security. Instead, safe boundaries and firefighting tactics are emphasized.
- DNV GL concludes that further electrical protection measures should be pursued within the array boundaries to reduce the risk of accidental shock and to improve operational decision-making, but not to serve as a rationale for intentional interaction. Firefighter training should emphasize this point.
- The FMEA evaluated mitigation options against practical scenarios in which personnel may be exposed to electrical shock hazards. Module level control, multiple-point disconnection of circuits from each other and ground, and solutions that limit or protect access to circuits all scored similarly as potentially effective measures to reduce the shock hazards within arrays. Further testing and analysis is recommended to develop more concrete conclusions.
- The study concludes that 1) revisions to the electrical code should include criteria for reducing the shock hazard while avoiding the prescription of specific product solutions; and 2) the analysis framework described is recommended as a model in the development of appropriate safety standards.

Considerations for ESS Fire Safety (Hill et al., 2017)

This report summarizes the main findings and recommendations from extensive fire and extinguisher testing program that evaluated a broad range of battery chemistries. The testing was conducted through much of 2016 on behalf of the New York State Energy Research & Development Authority (NYSERDA) and Consolidated Edison, as they engaged the New York City Fire Department (FDNY) and the New York City Department of Buildings (NY DOB) to address code and training updates required to accommodate deployment of energy storage in New York City. The main conclusion from the program is that installation of battery systems into buildings introduces risks, though these are manageable within existing building codes and firefighting methods when appropriate conditions are met. This report includes sections on guidance for first responders and findings related to codes and training. The topics addressed include:

- Guidance for First Responders
    - Considerations for Permitting and Siting
    - Considerations for Operations at the Scene
    - Guidance for Isolation and Overhaul
- Findings Related to Codes and Training
    - Fire Rating
    - Extinguishing
    - Class D and Deep Seated Fires
    - Cooling and Collateral Damage
    - Locations and Ventilation
    - Outdoor Locations
    - Indoor Locations (Penthouse or Dedicated Room)
    - GPM and CFM Requirement
    - Inspection and Monitoring
    - Clearances
    - Room Capacity Limitations
    - Project Development Considerations for Interaction with First Responders and AHJs
    - Considerations for Battery Chemistries that are not Li-ion

A primary finding from this report is that the equipment available to present day first responders can be considered adequate for battery firefighting with additional considerations.

Energy Storage Safety – Information for the Fire Service (US DOE, 2016)

The US DOE (2016) provides a fact sheet for the fire service developed in support of the DOE Energy Storage Safety Strategic Plan, noted earlier in this report. The fact sheet provides some background data on technologies, risks and hazards, and provides some guidance on incident preparedness activities, which are divided into two categories: engineered controls and administrative controls. In the fact sheet, administrative controls include activities such as pre-planning for an incident, codes and standards, and risk management tools, and engineered controls include aspects of the system and its installation such as fire suppression, storage system design, and fail-safes.

Fire Department Tactical Response Guidance (SFFD, 2012)
In addition to formal reports and training, the fire service issues internal operational guidelines for response to fire and other events across a wide range of hazards. This includes fire safety challenges of 'green' building materials, systems (technologies) and features. An example is from the San Francisco Fire Department on PVS and fire ground procedures.

Other Training Resources
The California Department of Forestry and Fire Protection (CAL FIRE), Office of the State Fire Marshal, developed a training curriculum on Fire Operations for Photovoltaic Emergencies. The curriculum reviews dangers and hazards associated with PVS and provides recommendations on how to protect fire crew members. (http://www.ncdoi.com/OSFM/RPD/PT/Documents/Coursework/PhotovoltaicEmergencies/Fire%20Ops%20W_PVs.pdf, accessed August 2020).

The International Association of Fire Fighters (IAFF) offers an online Solar PV Safety for Firefighters Course to help first responders feel safe and cognizant of potential fire hazards when responding to fires on PV-equipped structures (https://www.iaff.org/solar-pv-safety/, accessed May 2020).

The Interstate Renewable Energy Council (IREC) offers on-line training for firefighters and code officials on solar energy systems (https://irecusa.org/workforce-development/allied-solar-professions/pv-safety-for-fire-fighters/, accessed May 2020)

A partnership between the Canadian Solar Industry Association (CanSIA) and the Ontario Association of Fire Chiefs identified the need for firefighters to be properly trained for emergencies where solar panels are present and developed a Solar Electricity Safety Training Program that addresses safety considerations and firefighting protocols to successfully fight fires where photovoltaic (PV) or solar electricity systems are in place. This training program aims to assemble and widely disseminate core principles, tactical and rescue considerations and best practice information for firefighters, incident commanders and other emergency first responders to assist in their decision-making process in an effective manner at emergencies involving solar electricity. (https://www.oafc.on.ca/solar-electricity-safety-training-fire-departments, accessed August 2020)

Fire Service Magazines, Blogs and Related Media
The fire service has publications, social media and other networking and information sharing platforms. These resources often share information about events that occur and new issues and technologies to be aware of. Once such site is Green Maltese (http://www.greenmaltese.com/, accessed August 2020), which has several postings associated with fire safety challenges of 'green' building materials, systems and features.

US Fire Administration
The US Fire Administration (USFA) is cited here specifically in relation to its grants program, which can provide resources for research, training, risk management and related activities associated with fire safety challenges of 'green' building materials, systems and features (https://www.usfa.fema.gov/grants/, accessed August 2020). Grants are available under three programs: Assistance to Firefighters, Staffing for Adequate Fire and Emergency Response, and Fire Prevention and Safety. Grants under these programs have supported research undertaken by the UL FSRI noted above, the FPRF, academia (e.g., Meacham et al., 2017), and more. As new fire safety challenges of 'green' building materials, systems and features emerge, this should be considered as a resource for potential funding to support research, training and risk reduction in these areas.

10. Analysis and Research Needs

Chapters 1-9 represent an extensive update to state-of-the art knowledge concerning fire performance of 'green' attributes in buildings. The work has taken the report by Meacham et al. (2012) as a starting point. A significant amount of work has been done since 2012, not least in terms of regulations, standards and guidelines pertaining to 'green' attributes in buildings. This chapter endeavors to bring the work presented in the preceding chapters into a framework for illustrating knowledge gaps and research needs.

A fundamental aim of this review is to understand the extent to which unintended fire hazards and risks associated with 'green' attributes in buildings have been addressed, are being considered, and continue to emerge. The risk framework presented in Chapter 6 is at the core of this analysis, surrounded by three main themes: societal objectives (to create modern, 'green' buildings which do not endanger our climate); the attributes of the buildings and communities which express these societal objectives (materials, systems and design features); and, finally, control mechanisms that are put in place to ensure that these buildings and communities are fire safe (regulations, standards and guidelines). This framework can be pictured as a tetrahedron (triangular pyramid) with four faces, i.e., "Risk and Performance" at the base, and "Societal Objectives", "Attributes", and "Control Mechanisms" as the faces, see Figure 10.1a. For simplicity, the 2D projection of the 3D concept (see Figure 10.1b) is used throughout most of this chapter (alternative projections are shown in figures 10.2-10.4, where the other three dimensions take center stage.). In the figure captions, 'green features' is meant to reflect 'green' materials, systems and features as discussed in the report. As we consider each of these dimensions, gaps in knowledge are discussed based on the work presented in the preceding chapters.

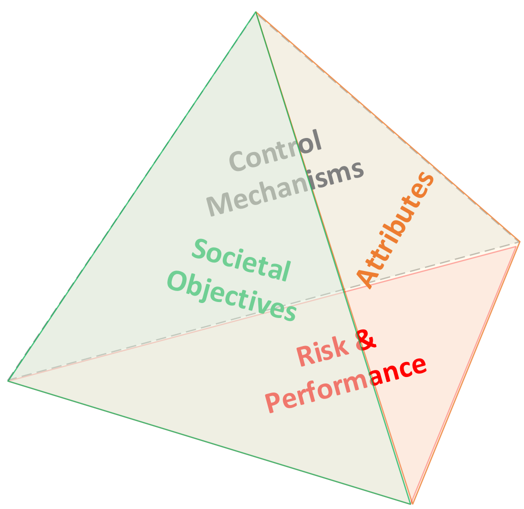


Figure 10.1a 3D Depiction of Risk Tetrahedron for Buildings with 'Green' Features

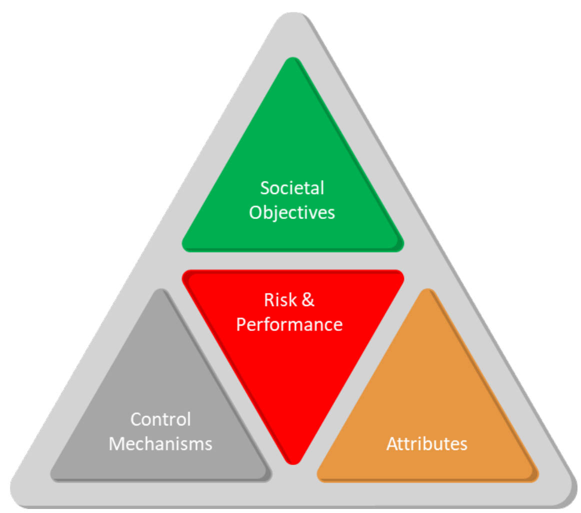


Figure 10.1b 2D Projection of Risk Tetrahedron for Buildings with 'Green' Features with "Risk & Performance" at the Center.

"Risk & Performance" forms the theoretical base of our tetrahedron as this is the hinge-pin on which much of the assessment is based. The literature study indicates that while fire hazards and risks, which have previously been identified, have been addressed in many regards, fire safety is still considered relatively late in the design process and does not always carry through to the operational phase of a building. Inclusion of fire safety in the early stages of product and system development, and in building or community planning and design, would help to alleviate many fire safety issues before they truly emerge, e.g. questions of material fire performance, system design, and first responder accessibility. In the 1990's the concept of design for the environment (DoE) or design for safety (DoS) became popular for consumer products. Similar concepts are applicable to building design to ensure inclusion of fire safety thinking as an integral part of any building project. Starting fire risk and performance evaluation early in the design process, even at the product or system stage, is necessary to ensure holistic fire safety. The relative risk framework presented first by Meacham et al. (2012) and updated in this report provides a starting point for identifying risks and their mitigation at various stages of product development, design, construction and maintenance of a building. As a first order tool, simply the fact that specific hazard and risk attributes are presented for consideration puts the issues on the table. While more information is still needed concerning the holistic performance of materials, systems and features identified in the matrices to quantify hazards and risks, the framework helps to identify where research and data collection may be warranted, and subjective indications of level of concern are provided as a means to help understand the importance of mitigating the hazard or risk. As with the relative hazard and risk ranking, the presented level of concern is based on the combined experience and expertise of the authors, as particularly informed by knowledge gained in this effort.

In 2012 it was concluded that research is needed to (a) develop a clear set of comparative performance data between 'green' and 'traditional' methods, (b), develop an approach to convert the relative performance data into relative risk or hazard measures, and (c) conduct a risk (or hazard) characterization and ranking exercise, with a representative group of stakeholders, to develop agreed risk/hazard/performance levels (Meacham et al., 2012). While this current effort identified examples of where progress has been made in some of these areas, well-vetted risk characterization process and assessment tools remain unavailable. For broad application, the hazard and risk characterization should be developed through the application of structured approaches based on available data and broad representation of experts in the field. Tools such as the Analytic Hierarchy Process (AHP) (Saaty, 1986), which have been applied in risk characterization and importance weighting approaches (e.g., Meacham (2000a); Meacham et al. (2017); Lamont and Ingolfsson (2018)), could serve as the basis for such tools. Experts should be drawn from a variety of disciplines, including sustainability and fire safety science and engineering, to achieve the necessary holistic risk and performance characterizations (e.g., Sánchez-Ostiz et al. (2014a); Sánchez-Ostiz et al. (2014b)).

With respect to data for use in any risk characterization or assessment tools, progress has been made, but several gaps remain. Unfortunately, many fire incident reporting systems still lack standard fields which would help identify fire hazards associated with 'green' building materials and systems, as well as their frequency and consequences. Free-text fields allow the inclusion of such information should the reporter of such data wish to do so. This has been used to identify and collate information on some systems, but the information is anecdotal rather than complete and more work is needed. Further, fire reporting systems are not comparable internationally with few reporting fields being directly comparable between countries. Work is presently underway to improve this situation by first making a full comparison between different incident reporting systems internationally and then making recommendations for harmonization. The NFPA is working together with numerous organizations internationally (including the report authors) under the leadership of Effectis France to conduct this project. More information should be available in the coming several years. A better understanding of response tactics with a focus on 'green' buildings and fire needs to be developed in a systematic fashion. While there has been some research largely focused on fire service interactions, largely from Underwriters Laboratories, Inc., there remain areas to explore more fully. Tactical response to specific systems or material performance is insufficient as 'green' buildings become more complex and response to one material or system can impact on interaction with another. In addition, as new technologies emerge, such as the recent explosion in use of large-scale energy storage systems (ESS), understanding the risks lag, let alone the firefighting tactical response. This is an example where being up front in technology development is critical.

The present study indicates that there are a number of areas which merit additional research to develop our understanding of the risks they represent, e.g. PV-systems, various façade systems, mass and high-rise wood construction, densification, energy storage systems, renovation practices and the use of recycled materials. Experience shows that in many, but not all, cases large scale fire incidents have occurred and that our experience of the risks such materials, systems or features is still limited. As more of these systems become integrated into single buildings, it may be that the potential for significant losses is growing. More research is needed to help understand the hazards and risks resulting from these complex buildings. Importantly, fire safety needs to become a baseline objective within new technology development, and not an afterthought to be addressed later.

Figure 10.2 moves our focus to "Societal Objectives". Historically, the fundamental societal objective in the context of 'green' buildings has focused on sustainability. Sustainability has traditionally been synonymous with environmental safety; but, in recent years has come to encompass the three established dimensions of environmental, economic and social sustainability. In this report we argue for the need to broaden our basic understanding of societal objectives as being many and not one, which must work together, and to include resilience into the context of Sustainable and Fire Resilient (SAFR) Structures. The underlying principle is that inclusion of risk and performance considerations into the overall assessment of whether particular structures meet design criteria across all societal dimensions allows for more robust or 'safer' solutions. As in the discussion of risk and performance, it is important to consider societal objectives in a holistic manner. Buildings typically do not exist in isolation but make up communities, which will also often have a desire to be both sustainable AND fire safe. While not specifically addressed in the review, with climate change contributing to the increase in number and intensity of wildland fires, the potential for impact in the wildland urban interface (WUI), and the need for sustainable and fire resilient communities, will only increase. Increased fire risk, along with materials and systems that could behave less than expected during a fire, is not a good combination.

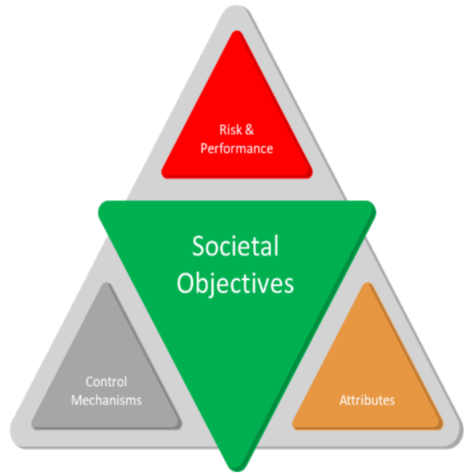


Figure 10.2 2D Projection of the Risk Tetrahedron for Buildings with Green Features with "Societal Objectives" at the Center.

Indications are that as early as 2021, the majority of new structures will be designed and constructed with 'green' materials, systems and/or features involved (Jones et al., 2018), which shows that 'green' buildings are becoming mainstream. With energy performance regulations, energy conservation codes, and 'green' construction codes, as well as energy conservation standards and 'green' certification schemes, there are myriad regulatory and market-based incentives to make buildings more sustainable. Some of the market focus on certification schemes, however, is still largely reserved for larger and costlier buildings, where developers, owners and managers are willing to invest in their 'green' status for triple bottom line benefits. Such buildings are likely to be able to also invest in fire safety as part of their overall functionality. At present, we lack the type of market-based incentives that 'green' certification provides in the fire safety performance realm. While some corporations have their own guidelines, most building construction is governed by regulations and insurance requirements, neither of which explicitly provide benefits for achieving fire performance that is higher than minimum requirements.

However, if the idea of SAFR structures resonates, the SAFR framework might be a way to develop incentives for fire resiliency along with environmental sustainability. However, if the concept of SAFR structures is to become mainstream, it is necessary to ensure that our understanding of the risks and performance of 'green' materials, systems and features is sufficiently well developed to ensure sound construction practices and facility operations and maintenance within the 'green' market. This is a particularly important point given that the vast majority of buildings are not new, but are already existing, and often outside of strict regulatory compliance for some types of rehabilitation and renovation. The fire resiliency of buildings needs to migrate into the realm of building renovation for sustainability, and to do so, it is critical to understand the implications of material, technology and design choices when the majority of the structure is already standing. New models and best practices to migrate existing buildings stock safely into the modern 'green' building paradigm is necessary.

Digitalization could be a key to facilitating such a migration to set existing and new buildings at least partly on a level footing through leveraging digital platforms.

Building Information Models (BIM) are increasingly adopted in the design and construction phase of modern buildings but only in a small percentage of cases are such models used to assess the overall sustainability and fire safety of the building. It is unclear to what degree BIM is employed in renovations or new buildings, but it does hold the potential to facilitate the sound transfer of building information through different stages of both building paradigms. More work is needed to develop the SAFR concept and apply this concept to expanded BIM applications that include assessment of sustainability parameters as carbon-footprint and include key fire safety engineering (FSE) design parameters and systems. The inclusion of FSE systems and considerations into BIM would facilitate the development of truly fire safe and sustainable buildings. The tools exist but broader adoption is necessary to build experience and comfort with their application.

The use of sustainable materials, reducing energy consumption, and reducing the overall carbon contribution to the environment, are all key components to 'green' or sustainable design. Likewise, use of fire safe materials and systems provides a good starting point for the design of fire safe buildings. SAFR structures need to holistically include both considerations. While 'simple' in concept, materials, systems and features are often complex composites of individual components, just as the buildings themselves represent complex combinations of materials and systems. The way the current regulatory systems are working, testing and assessment of materials, systems and features occurs within the silo of the regulated performance, such as 'energy performance' or 'fire performance', and the holistic 'energy and fire performance' objective might be missed. Furthermore, test methods are often developed for specific materials or components, and not the complex 'system of systems' that may actually be installed (such as a complex façade system). Methods to understand how to relate component performance to composite performance are urgently needed. Lessons might be learned from digital systems using artificial intelligence, which allow the component-based design of bespoke systems using interactive customer- based design platforms. Some work has been done on intelligent BIM systems (see e.g., Aljebory and QaisIssam (2019); Zhang (2020)); but, the use of AI to improve fire safety is still a largely new field of research.

While client demands for 'green' buildings appear to be increasing, there remain numerous barriers to the full adoption of 'green' buildings in all projects. When surveyed concerning key drivers and barriers, many companies cited the lack of political support through incentive schemes, real or perceived higher investment costs, lack of training concerning 'green' materials and systems on the market, and the lack of building lifetime business calculations to show the benefits of 'green' buildings (Jones et al., 2018). Accepted models to calculate the life-cycle costs of a 'green' building need development. Data concerning intangibles such as improved image of businesses housed in 'green' buildings need to be developed together with realistic costing methods to compare building investments to running maintenance costs.

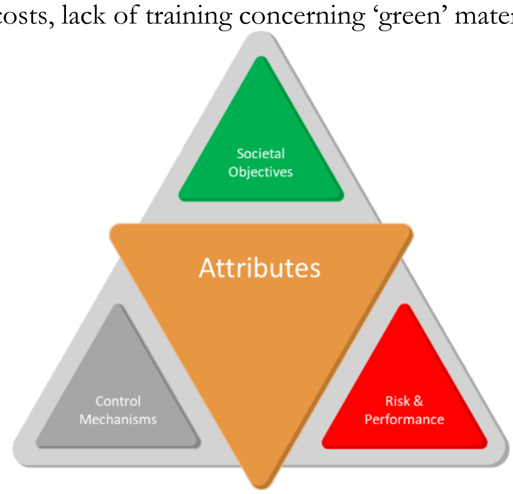


Figure 10.3 2D Projection of the Risk Tetrahedron for Buildings with Green Features with "Attributes" at the Center.

Materials, technologies, systems and features can collectively be referred to as the "Attributes" of a building. These attributes are designed to meet societal objectives and, just as for societal objectives, these need to be considered in terms of risk and performance. Figure 10.3 depicts the 2D projection of the risk tetrahedron, now with "Attributes" at the center of the diagram. The literature survey presented in Chapter 4 shows that new materials and systems are constantly being developed. Fire incidents reported in Chapter 3 indicate that sometimes the adoption of such systems can have unexpected consequences when safety considerations are not considered early in the development phase or where unexpected combinations of materials are used to create and install systems outside of the original specifications. Both for traditional attributes and new development, it is clear that these need to be tempered by consideration of risk and performance and control mechanisms need to be developed to address their application.

Three key trends connected specifically with attributes are the need for renovation of an aging building stock, presence of new technologies continuously being introduced, and the increased desire to develop a circular economy. The aging building stock implies that renovation will continue to be an important part of building maintenance. Numerous fire risks manifest during the renovation of a building, e.g. existing fire safety systems might be taken off line during a renovation, new material combinations could occur for which the building safety systems were not designed, new and old technology meet causing potentially unexpected consequences. As noted in Chapter 4, there are continuous innovations in 'green' and sustainable technologies. Since 2012, the explosion of ESS in buildings, advancements in BIPV, and move to mass timber are all important contributors to sustainability, which have all introduced some new level of fire safety concern. Innovation for sustainability is not going to, and should not, stop. However, it is important to embed the need for fire safe performance of sustainable materials and systems into their design. In the development of a circular economy, recycled material is increasingly desirable. While components are developed from recycled material or existing products are re-purposed for new applications, it is important to consider fire safety. Previously compliant material may no longer be compliant when used in new applications. Recycled materials, whether used as filler in concrete or as insulation material may have varied quality and be difficult to reliably source, meaning that the material performance can be unpredictable. This could translate to uneven fire safety performance. Systems for the approval (testing), inspection and compliance of such material need to be developed. It is reasonable to assume that systems developed with mass manufacturing of products with uniform supply streams will not be immediately applicable to recycled materials.

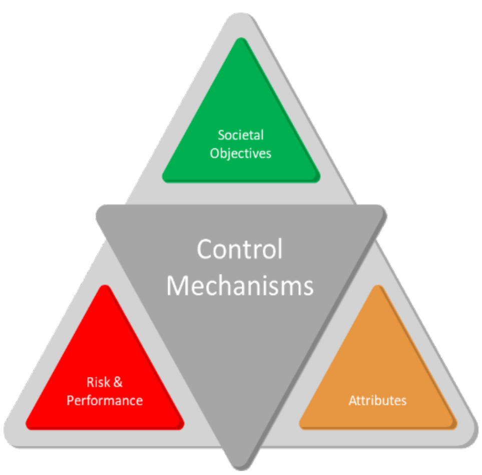


Figure 10.4 2D Projection of the Risk Tetrahedron for Buildings with Green Features with "Control Mechanisms" at the Center.

The final dimension of the framework presented here, deals with the question of Control Mechanisms. Figure 10.4 shows the 2D projection of the risk tetrahedron with this dimension in the center. Control Mechanisms can be seen to be the method by which democratic societies impose safety provisions on materials, products and systems designed to meet specified societal objectives. In the case of products and services, there is a long tradition of establishing performance requirements through standards or guidelines to define acceptable levels of performance for market accessibility. There are a variety of approaches to the development of control mechanisms from component testing to end use testing. In the case of many complex products, component testing may be adopted due to the prohibitive cost associated with testing all possible combinations of components in the potential end use. Typical for many control mechanisms is that they include aspects of testing, inspection and compliance over a period of time to ensure that established levels of safety are maintained over time.

Unfortunately, such systems are often reactive, with standards being developed as a reaction to incidents or based on the development of innovations which have met the market but where there are indications that risks might exist but remain to be manifest. Also, if the test and analytical methods are lacking, there may be gaps in the regulations and resulting building designs. There is a clear need for such control mechanisms to become more proactive and reflect a socio-technical systems (STS) approach for ensuring fire safety ahead of the curve of development of the product, building or service (e.g., Meacham (2014); Meacham (2016); Meacham and van Straalen (2018); Meacham and Strömgren (2019); van Hees et al. (2020)). Performance requirements, rather than banning specific materials or chemicals in testing standards, help in the development of proactive standards. Performance standards are applicable to a range of existing materials and those yet to be imagined. There is a tendency after major fire incidents for the market (and not least the regulators) to react to specific materials by implementing bans rather than to consider whether the testing regimes are allowing the wrong type of material to pass and to adjust the control mechanisms rather than resort to short-sighted product bans. There is a need for research into robust performance standards, the applicability or component or end-use testing, in support of broader adoption of fire safety engineering in the development of safe and fire resilient (SAFR) structures. Already, we see the development of manufacturing methods or materials and systems which will challenge our established control mechanisms, e.g. biomaterial, phase-change material, graphene, CCS, 3D-printing, just to name a few. As new material and systems are only bounded by the imagination of the entrepreneurs from which they stem, we can be certain that new challenges to established control mechanisms are likely in the future. Finally, the fire service is the group that is left to address fire safety hazards that are not controlled prior to building completion. As noted in Section 9, more information to inform firefighting tactics as become available in recent years. However, as with product development, fire service issues need to be moved up earlier in the design process, and not stay an afterthought.

To summarize, this chapter has related the work in the preceding chapters to a 'risk tetrahedron' to facilitate the identification of knowledge gaps and research needs. Many of these research needs are related to each other, e.g. the need for new risk models and data input for such models. The next chapter will both provide an overall summary of the findings in the study as a whole and build on the analysis presented in this chapter to provide suggestions for future work.

11. Conclusions and Future Work

While significant work has been undertaken since 2012, and advancement has been made towards more fire safe implementation of 'green' (sustainable) attributes into buildings, gaps exist, and research, development and technology transfer is still needed in a number of areas. Gaps in understanding and assessment tools mean that in some cases there has been insufficient development of design guidance, standards and regulations. Based on the overview conducted and the analysis in the previous chapter a number of key suggestions for future work are given below.

<u>Integration of 'green' (sustainable) building attributes into fire incident reporting systems.</u>
While more fire incident data are available than was identified in 2012, there remains significant gaps in reporting on fire ignitions and contributions of 'green' (sustainable) attributes of buildings, and how sustainable planning and building features may have impacted the severity of a fire or the response of the fire service. While some major events such as the Grenfell Tower fire capture attention for some time, it may be that there are hundreds of fires involving sustainable building materials, systems (technologies) and features that are not identified, and therefore not available to inform mitigation options. Steps that can be taken include:

- Broaden the input data fields on fire incident reporting systems to better capture 'green' / sustainable building materials, systems (technologies) and features that are suspected of contributing to fires
- Develop better fire incident capture systems, which integrate smart phones and other technologies to facilitate photos, videos and other data which can help better understand the fire event

<u>More robust and appropriate test methods, which yield engineering data, for assessment of material, component and systems performance.</u>
Closely related to the above, while some progress has been made on better understanding fire performance of sustainable building materials, systems and technologies, some of the current standardized testing may not capture the fire safety hazards and risks of the materials, systems and technologies in use (i.e. real life scenarios) well enough. Furthermore, the outcomes of the tests are not always conducive to engineering analysis through computational methods; and given the cost of mid- and full-scale testing, relevant data for the extrapolation or interpolation of results using engineering methods, are not developed. If there are inadequate data to inform regulation and support engineering tools, gaps may exist in resulting regulation, standards and guidance. The fire performance of complex façade systems is but one example. Data for engineering analysis is needed for all components, and the means to assess real-scale system performance is required. Steps that can be taken include:

- Development of standardized fire tests that deliver data that can be used in engineering analyses and computational analyses
- Development of 'appropriate-scale' fire test methods to deliver more robust data on expected performance in real-scale applications
- Widespread adoption of new façade fire tests, that represent actual fires and have appropriate acceptance criteria, should be facilitated.
- Develop joint funding proposals, e.g. to NIST, RISE, BRE, BRANZ, etc. for development of new test and measurement standards.

<u>Integration of the need for fire performance consideration into 'green' (sustainable) materials, technologies and features research and development.</u>
As emerging technologies such as carbon capture systems, new structural materials, BIPV and more are developed, fire safety needs to be at the front end of the design process, and not an afterthought. Consider what happens as building integrated photovoltaics system (BIPV) technology becomes fulling integrated into façade systems, providing a potential source of ignition that is continuously available. In product design, like building design, the cost to mitigate at the end is much higher than at the outset. This will require a change in

thinking within the product and building design communities, although this can build on a tradition of product design for the environment (DoE) adopted in consumer products previously. Steps that can be taken include:

- Workshops / working groups comprised of delegates from the building and energy technology research, design and development communities, the architectural design community, the fire safety research and design communities, and the fire service community to develop common understanding, vocabulary, research needs, tools for practice, regulatory mechanisms and extra-regulatory guidance associated with emerging 'green' / sustainable building materials, systems (technologies) and features.
- Develop methodology to include safety and sustainability simultaneously, e.g. the SAFR concept (dealt with separately below)
- Develop multidisciplinary funding proposals, e.g. National Science Foundation for fundamental research.

<u>Robust risk and performance assessment methods and tools, which are founded on broad expert stakeholder knowledge and experience, available data, and expert judgment where data are lacking.</u>
One could argue that, by definition, emerging technologies will have many unknowns, and therefore risk. While testing, such as component level fire testing, can provide insight into part of the scenario, it may be insufficient to understand the overall fire performance. Risk-informed performance-based methods are needed to provide insight into the range of possible realizations of complex systems designs, and to inform mitigation strategies to control the risks to tolerable levels. Without all of the physical or statistical data needed to make judgements with very small bands of uncertainty, expert judgment, broad stakeholder deliberations, and use of available data will be needed. Methodologies that appropriately integrate these components will be essential. Steps that can be taken include:

- Workshops / working groups comprised of delegates from the building and energy technology research, design and development communities, the architectural design community, the fire safety research and design communities, and the fire service community to develop common understanding, vocabulary, research needs, tools for practice, regulatory mechanisms and extra-regulatory guidance associated with characterizing and assessment risk and performance of existing and emerging 'green' / sustainable building materials, systems (technologies) and features.
- Develop joint funding proposals, e.g. to National Science Foundation and others for fundamental research; NIST, BRE, RISE, BRANZ and others for risk and performance assessment tools for fire safety engineers; USFA and others for risk assessment methods for the fire service.

<u>Better tools for holistic design and performance assessment, taking advantage of BIM and other technologies that are defining the future of the construction market.</u>
Fire safety design is not, and should not, be an isolated practice. Rather, it is part of a holistic design of a building. Better analysis and design tools for support of multi-dimensional performance assessment will be needed, and more use of technologies such as BIM, which are already widely used in the design practice, will be needed. As the industry moves to modular, or prefabricated prefinished volumetric construction, analysis and design decisions will be made 'in the shop' prior to manufacturing of components for shipment to the site and assembled into a finished building. Not only will the design technologies be essential, but also the means to assure the assembled building has addressed key issues, such as fire protection of connections, fire protection of void spaces, and the like. If such a building has issues that need to be 'fixed' after construction, the costs could be significant. Steps that can be taken include:

- Workshops / working groups comprised of delegates from the architectural design community, the BIM development community, and the fire safety design community to develop common understanding, vocabulary, research needs, and tools for practice related to BIM and other design-to-manufacturing and prefabricated prefinished volumetric construction approaches.

- Develop joint funding proposals, e.g. to National Science Foundation for fundamental research; NIST for risk and performance assessment tools for fire safety engineers; USFA for risk assessment methods for the fire service; industry and practitioners to fund the expansion of BIM to support sustainability and safety features to a greater degree.
- Generate data for BIM models.

Transition to more holistic, socio-technical systems approaches for building regulatory systems, which consider the diversity of societal and market objectives for building design, construction and lifetime operation.
The current building regulatory system remains largely structured following the 'regulation by event' approach that has been used for the past 100 years. Regulatory development is undertaken largely by disparate experts working in individual silos with the hopes that the outcome is a horse and not a camel. There are numerous societal and market objectives for building design and construction, and there should be requirements for lifetime performance in operation, across a wide spectrum of aspects, including sustainability and fire resiliency. Investigations into fires such as the Grenfell Tower point in some ways to how fortunate we are that catastrophic fire remains a relatively rare event. Evolving the building regulatory system to a more socio-technical systems approach can help better identify and address the diversity of objectives a building is expected to achieve throughout its lifetime. Steps that can be taken include:

- Workshops / working groups comprised of delegates from the architectural design community, the fire safety research and design communities, building regulatory community, the fire service community and industry to develop common understanding, vocabulary, research needs, and practical implementation issues associated with development and transition to a more socio-technical systems approach to regulation of building fire safety.
- Develop joint funding proposals, e.g. National Science Foundation for fundamental research; foundations supporting resilient design principles.

Further development and articulation of the SAFR buildings concepts and its societal and economic benefits.
The concept of sustainable and fire resilient (SAFR) buildings has been proposed as a way to better integrate sustainability and fire safety performance objectives in building design and performance. A 'green' building is not so 'green' if it burns down and needs to be reconstructed. A fire sprinkler system is not just a life safety system but is a means to minimize environmental impact should a fire occur. Steps need to be taken to develop concepts that deliver on both objectives in a holistic manner. Steps that could be taken include:

- Workshops / working groups comprised of delegates from the sustainable design and the fire safety design communities to develop common understanding, vocabulary, research needs, tools for practice, regulatory mechanisms and extra-regulatory rating schemes.
- Develop joint funding proposals to relevant entities, e.g. National Science Foundation for fundamental research; foundations supporting resilient design principles.
- Advancing the concept of SAFR structures into the educational curricula for all stakeholders involved in design, construction, use and operation of buildings to maintain the societal desire for sustainable and fire resilient buildings.

Appendix 1: List of Databases in LUBsearch

Licensed databases in LUBsearch

- Academic Search Complete (ASC)
- AMED - Allied and Complementary Medicine Database
- Art & Architecture Source
- ATLA Religion Database with ATLASerials
- Avery Index to Architectural Periodicals
- Bibliography of Asian Studies
- Business Source Complete
- CINAHL Complete
- Communication Source
- Criminal Justice Abstracts with Full Text
- EconLit
- Economist Historical Archive
- eHRAF Archaeology
- ePublications
- ERIC
- FSTA - Food Science and Technology Abstracts
- GeoRef
- GreenFILE
- HeinOnline
- Henry Stewart Talks
- Humanities International Complete
- IEEE Xplore Digital Library
- IMF eLibrary
- Inspec
- LGBT Life with Full Text
- Library, Information Science & Technology Abstracts with Full Text
- Literary Reference Center
- MathSciNet via EBSCOhost
- MEDLINE
- MLA International Bibliography
- New Testament Abstracts
- OECD iLibrary
- Old Testaments Abstracts
- Oxford Competition Law
- Philosopher's Index
- Political Science Complete
- PsycCRITIQUES
- PsycINFO
- PsycTESTS
- Regional Business News
- RILM Abstracts of Music Literature
- Rock's Backpages
- SAE Technical Papers

- SAGE Video
- Scopus
- Short Story Index (H.W. Wilson)
- SocINDEX with Full Text
- Sustainable Organization Library (SOL)
- Teacher Reference Center
- Urban Studies Abstracts
- Very Short Introductions Online (Arts and Humanities)

Open-access databases in LUBsearch

- Aphasiology Archive
- Archive of European Integration
- arXiv
- British Library EThOS
- CogPrints
- Directory of Open Access Journals
- eScholarship
- Industry Studies Working Papers
- LUNA Commons
- Minority Health Archive
- Networked Digital Library of Theses & Dissertations
- OAPEN Library
- OJS vid Lunds Universitet
- Open SUNY Textbooks
- Open Textbook Library
- Persée
- PhilSci Archive
- SSOAR - Social Science Open Access Repository
- SwePub

Free Index/Catalogues in LUBsearch

- Publications New Zealand Metadata
- SveMed+
- Swedish National Bibliography

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