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Pre-normative Research on Fire Safety of Building Integrated Photovoltaics (BIPV)

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Executive Summary

Building-integrated photovoltaics (BIPV) offer important contributions to the achievement of net-zero energy buildings. BIPV modules can either be attached to building elements, or integrated with building elements, each of which attracts different National Construction Code (NCC) requirements. BIPV systems offer dual functions as building elements and solar energy-generating components. Fire safety is a topic of primary interest in relation to the application of BIPV in buildings, and it is essential that their use as building facades and roofs to replace conventional building materials does not adversely affect the safety of building occupants and fire fighters. Few studies exist which enable the building industry to understand the fire hazards of BIPV and identify the requirements applicable to BIPV modules, both in terms of electricity production and as building elements of the national regulatory landscape and context. This report will help stakeholders to clarify the regulatory framework for fire safety, and support Australian BIPV project planners and implementers in the application of the main prescriptions of the current regulatory framework.

BIPV applications on building surfaces can be categorized into two types. While one type of BIPV application is to attach to building elements, another one is as a part of or wholly the building elements. The main causes and mechanisms of the fire hazards of BIPV include ignition of BIPV modules, fire propagation, and hazards to occupants and fire and rescuepersonnel under conditions of fire. BIPV modules should comply with fire safety requirements in two respects: as electrical products and as building elements.

The entire building elements (attached to or integrated with) with BIPV modules, not only sole BIPV modules, should comply with the relevant requirements of the National Construction Code (NCC). There are three pathways to demonstrate Performance Requirements in the NCC: (1) Deemed to Satisfy (DtS) Provisions, or (2) Performance Solutions, or (3) a combination of DtS Provisions and Performance Solutions. As part of a building integrated electricity production system, BIPV must comply with the regulatory requirements of both building fire safety and electrical safety.

A comparison of the standards and regulations applicable to BIPV modules in different countries will provide an overview for Australian regulators and BIPV suppliers and assist with clarifying differences in regional fire safety requirements. This report will help stakeholders to understand the complex fire safety normative framework, and present a summary of current fire safety requirements for BIPV modules as electrical products and building elements at the international, Australian, and Victorian levels.

This report also points out future research directions which will assist the development of BIPV fire prevention strategies in Australia. Eighteen future research directions are discussed from four major aspects: (1) Mitigation of fire spread, the impact of building design strategies, the hazard of debris, and the mitigation of electric hazards; (2) Test configuration, including specimen size, active specimens in the tests, electrical shock, and suggestions for common structures of specimens; (3) Product innovation, focusing on the protection of electrical components and alternative materials for BIPV modules; and (4) Regulation, including suggestions on AS 5033, references to overseas fire safety test outcomes, and relevant Deemed-

to-Satisfy Provisions associated with BIPV.

Section 1 Introduction

1.1 Background

Buildings are responsible for 19% of total energy use and 18% of direct carbon emissions in Australia (energy.gov.au., 2022). Solar photovoltaic (PV) technology is recognised as one of the most favourable renewable energy applications for buildings (Mazziotti et al., 2016). In recent years, the most common PV application is building-attached PV (BAPV) systems, in which PV panels are mounted on the surface of a constructed roof or wall. With the development of PV technology, PV modules are altering building skins by converting external walls, roofs, windows, as well as barriers and ancillary elements, into energy-generating assets (Ko et al. 2022). Building-integrated photovoltaics (BIPV) modules can either be attached to building elements, or integrated with building elements, each of which attracts different NCC requirements. BIPV systems offer dual functions as building elements and solar energy-generating components (Heinstein et al., 2013; Aelenei et al., 2014), offering important contributions to the achievement of net-zero energy buildings (Henemann, 2008).

BIPV has unique advantages over other distributed renewable technologies, such as wind turbines, geothermal energy, hydro, and biogas (Tazvinga et al. 2017). Because the BIPV modules are true construction elements, serving as building exteriors such as roofs, façades or skylights, BIPV also provides functions including building protection, aesthetic improvement, thermal comfort and electricity generation (Zhang, Wang & Yang 2018). Further, solar energy generation at the site of the load, rather than remotely, supports 'behind-the-meter' use of energy, which avoids transmission costs and losses. However, the uptake of BIPV has been slow. Between 2014-2019, less than 2 MW of BIPV was installed in Australia, compared with 7.4 GW of roof-mounted PV (APVI, 2015-2020). Principal barriers include building codes, and performance requirements which are designed to ensure the safety of building occupants, and testing methods which are not adequate to ensure the safe implementation of BIPV. As it is a technology deployed on residential and commercial buildings, it is critical that BIPV does not reduce the level of occupants' safety, health, amenity, accessibility or the sustainability of buildings. In order to expand the scope of application of BIPV, more adequate and clearer safety requirements are increasingly required. Of these requirements, the most urgent is fire safety. Due to the combustibility of BIPV modules, potential fire hazards of BIPV on buildings can be classified as ignition and propagation of fire. Fire hazards from BIPV can threaten the safety of building occupants, firefighters, and entire neighbourhoods (Cancelliere, 2016).

1.2 Problem statement

Two main aspects of fire safety requirements are relevant to BIPV, namely fire safety requirements relevant to the electricity production components and fire safety requirements relevant to the building elements[1] that BIPVs are used to (Bonomo, Saretta & Frontini 2018). Thereby, BIPV applications must comply with the requirements for fire safety of the relevant national organisations and local authorities.

[1] Building elements in this report include roofs and skylights, loadbearing and non-loadbearing walls, ceilings, floors, windows and other openings, atriums, and ancillary elements.

Internationally, the fire performance of current PV modules is mainly evaluated by two standards: IEC 61730, UL 1703. From another perspective, as a building element, EN 13501 is used to evaluate the building elements that BIPV apply as in European countries. However, these tests are either PV-related or overseas-specific and differ from Australian tests for building elements. Therefore, it is important to clarify the NCC requirements relevant to the fire safety of BIPV , as well as the potential pathways to satisfying these requirements.

In Australia, the use of BIPV in buildings must satisfy the Performance Requirements of the NCC, which sets the minimum levels for fire safety, health, amenity, accessibility and sustainability of certain buildings. Each State and Territory has its own legislative and regulatory requirements that may govern the use of BIPV. These, including electrical safety regulatory requirements, must also be complied with. Therefore, a crucial issue with the fire safety of BIPV is the knowledge gaps. There is no explicit, public information on the compliance of current products with Australian building regulations, which are quite complex.

The use of combustible BIPV on façades/external walls and roofs must ensure the fire safety of building occupants, facilitate firefighting, and prevent the spread of fire to adjacent properties. The presence of BIPV in buildings could worsen the pre-existing level of fire hazards, because it may modify the propagation of fire, interfere with the venting of smoke and other combustion products and inhibit fire suppression operations. This fire hazards may cause unsafe conditions for building occupants. In addition, it introducesing the further additional hazard of electric shock from live elements that may impact fire and rescue operations. Owing to the limited presence of BIPV projects and products in Australia, building professionals lack sufficient knowledge to judge the fire hazards of buildings with BIPV. They need to understand the performance of building elements with BIPV under fire conditions and its behavioural impacts on other fire safety features of the building. They need clear maps of international and national standards related to BIPV fire safety.

Limited studies are found from literature to enable a thorough understanding of the fire risks associated with BIPV and identification of the requirements applicable to BIPV, both as elements for electricity production and as building elements, originating from the national regulatory landscape and context. This report aims to help stakeholders to understand the regulatory framework for fire safety and supports Australian BIPV project planners and implementers in the application of main prescriptions derived from the current regulatory framework. Furthermore, this report informs future research directions.

1.3 Research Objectives

This study has the following objectives:

- Support stakeholders in understanding the causes and mechanisms of BIPV fire;
- Provide an overview of the relevant requirements in Section C of NCC volume 1 and the overview of relevant tests for fire resistance of applicable building elements ;
- Provide an overview of the electrical safety requirements for BIPV modules based on a review of Victorian regulations/legislation;

- Compare the fire safety requirements for the application of BIPV in different countries and present an overview of current fire safety requirements for BIPV as electrical products and building elements at international, Australian, and Victorian levels;
- Identify gaps in addressing the fire risks of BIPV in buildings and recommend future research directions and hazard mitigation methods for the fire safety of BIPV.

The audience for this report includes policy makers, fire safety engineers, fire rescue organisations, building surveyors, BIPV manufacturers, and researchers.

1.4 Significance of the research

The energy consumption of the global building sector (which includes both residential and commercial structures) will increase by 65% between 2018 and 2050, from 96,010 quadrillion to 146,653 quadrillion joules (Gholami et al., 2020). The continuing demand for green building initiatives has led to market demands for PV beyond the rooftop. This project explores the most significant acceptance of renewable energy in modern urban life represented by the installation of solar building surfaces, which is essentially the deployment and integration of PV panels on possible surfaces of buildings. According to the IEA (2002), the potential production of solar electricity on building envelopes in Australia is 84.057 TWH/y, sufficient to supply 46.1% of total electricity consumption in buildings (i.e. 182.24 TWh/y) (IEA, 2002). With many new buildings being developed in the last few decades, and increasing energy demands in buildings, the benefits of using BIPV in Australia are more significant than 20 years ago. This potential is equivalent to a reduction of 6.9 million tonnes of carbon dioxide per year (Department of Industry, Science, Energy and Resources, 2020), which will have increased significantly with the large number of buildings completed since 2002. However, to date BIPV in Australia has been limited to rooftop integration of relatively conventional PV modules in a few domestic buildings, and a small number of emblematic demonstration projects.

Fire safety is a topic of primary interest in relation to the application of BIPV in buildings. The appropriate levels of safety and reliability during a building's life cycle require the investigation of innovative technologies and approaches to the protection of buildings. In particular, the fire resistance of building elements with BIPV modules is a crucial issue for the mitigation of fire safety hazards. The research outcomes will enrich our current understanding of how to investigate the impact of BIPV on fire performance and how building designs and standards can support technology deployment. The study will propose research and investment directions for future BIPV applications in Australia.

The application of BIPV on buildings requires accurate performance assessment in accordance with NCC requirements and the relevant Australian standards. According to the report 'Fire Safety of Solar Photovoltaic Systems in Australia' by the Alternative Technology Association (ATA), the number of fire accidents caused by solar panels in Australia increased significantly from 2009 to 2014 (ATA, 2016). In other words, as the PV market has increased, so has the number of fires reported (ATA, 2016), highlighting the need for a detailed fire prevention policy, including fire protection systems, especially regarding the interaction of PV with a building's skin. This study presents essential information for comparison with international and national fire test procedures and PV module installation requirements in building and related fire codes, thereby informing the development of policy and industry standards.

The introduction of requirements and test methods related to fire resistance is expected to accelerate the adoption of BIPV in Victoria, strengthen the BIPV industry and enable the replacement of building surfaces, whether new or renovated, with reliable solar-power generation options. The research outcomes will inform the assessment of compliance with selected sections of the NCC to enable suitably qualified and competent professionals to understand and mitigate the potential fire hazards of building envelopes. This project will provide ways for policymakers to understand BIPV fire hazards. To date, limited empirical research has been conducted on evaluating the fire safety issues of solar building surfaces. The study will also help authorities assess the robustness of existing or proposed standards and policies for developing sustainable building surfaces.

1.5 Research scope and limitations

This is a scoping research project with limitations in its scope, as follows:

- This report focuses on the requirements for Class 2-9 buildings due to BIPV design complexities in these buildings. Building classifications used in this report are based on NCC definitions; the version of the NCC that is being used in this project is NCC 2019. Class 1 buildings are not considered in this research.

- This report focuses on the fire resistance and combustibility requirements outlined in Section C in NCC Volume 1 for external walls and skylights. When a BIPV module is applied to a building element in Australia, the building must meet all requirements of any relevant part of the NCC, including structural, weatherproofing and energy efficiency requirements in addition to fire safety requirements. Apart from fire resistance and combustibility requirements, other fire safety requirements may also be applicable.

- This study reviews the Performance Requirements and relevant tests based on DtS Provisions and Verification Methods in Section C. However, since this is a scoping research project, it does not outline detailed information in the NCC, and includes limited information on the pathways available to meet these requirements in Australia. More comprehensive industry consultation is needed to develop industry guidelines, as stated in the section on Future Research Directions.

- Although batteries, isolators, and inverters may be critical fire hazards in electrical systems, they are common components in most renewable electricity systems rather than solely in BIPV systems. Installation of batteries with BIPV is not compulsory in buildings. Isolators and inverters should be installed in BIPV buildings, but are not considered to be part of BIPV modules. As the BIPV module is a unique component in the study area, this report only focuses on BIPV modules (including the BIPV laminate, junction box and associated cabling and wiring).

- BIPV applications in this report are considered building elements, as specified by the NCC, to which BIPV modules can be applied, including external walls, windows and openings, barriers, roofs, and ancillary elements.

- Although this report summarises the most relevant normative documents, it is not intended as an exhaustive source of information nor a replacement for the official documents provided by authorities and associations.

1.6 Report Structure

This report is structured as follows:

- Section 2 presents the research methodology used in this research;
- Section 3 provides an overview of BIPV applications and relevant fire hazards;
- Section 4 illustrates the hierarchy of legislation in relation to building and electrical acts, regulations, standards in Australia
- Section 5 presents an overview of the fire resistance and combustibility requirements in Section C of the NCC for external walls and skylights;
- Section 6 provides an overview of the relevant electrical standards for BIPV/PV fire hazard with reference to the NCC;
- Section 7 presents a comparison of fire safety requirements for the adoption of BIPV modules in different regions;
- Section 8 suggests possible research directions for future investigations.

Section 2 Research Methodology

This study reviews the latest academic and industry publications on BIPV/PV fire safety. The purpose of the literature review is to understand the main causes and mechanisms of fire hazards associated with BIPV modules and the impacts on stakeholders caused by BIPV fires in relation to installation, operation, maintenance, and firefighting operations. This study also reviews BIVP product information on global BIPV manufacturers' websites to understand what fire safety certifications have been awarded to the current BIPV products, and the fire tests they are subjected to.
This study also reviews the fire resistance and combustibility requirements of the NCC for external walls and skylights. Regarding electrical standards, this study reviews AS 5033 and AS 3000, which include the requirements of PV mounting and the common requirements for electrical systems, respectively. The NCC is the core regulation reviewed in this study in order to understand the fire safety requirements which must be met by BIPV in Australia. AS 1530.1, AS 1530.3, AS 1530.4, and AS 5113 are also reviewed (see Section 5) in the context of fire safety requirements and combustibility per NCC Volume 1 Section C (see Appendix C for a list of Standards referenced in this report). Furthermore, international and overseas standards related to the fire safety of BIPV modules are also reviewed. The purpose of the review of international standards review is to compare the fire safety requirements of Australia with those of other countries.

In addition to the literature review, forty interviews of nineteen domestic participants and eleven overseas professionals, are conducted in order to understand the impacts of fire and the complex details in national and international standards, and to explore future research opportunities. Profiles of the interviewees are shown in Table 2.1, where they are classified in six stakeholder groups.

Table 2.1 Interviewees' profiles

Group		Interviewee ID	Organisation type	Working experience (Years)	Relevant sections
Electrical area	Australia	Interviewee 1	Industry organisation	17	Sections 4, 6, and 8
		Interviewee 2	Government department	11	
		Interviewee 3	Educational institute	13	
		Interviewee 4	Government department	13	
Fire safety engineers	Australia	Interviewee 5	Engineering firm	3	Sections 3, 5, and 8
		Interviewee 6	Engineering firm	20	
		Interviewee 7	Engineering firm	17	
		Interviewee 8	Engineering firm	23	
		Interviewee 9	Engineering firm	6	
		Interviewee 10	Engineering firm	8	
		Interviewee 11	Engineering firm	6	
		Interviewee 12	Engineering firm	9	
		Interviewee 13	Engineering firm	20	
	Overseas	Interviewee 14	Government department	18	Sections 7 and 8

Group		Interviewee ID	Organisation type	Working experience (Years)	Relevant sections
		Intervieweev15	Government department	7	
		Interviewee 16	Educational institute	16	
		Interviewee 17	Engineering firm	19	
		Interviewee 18	Educational institute	15	
		Interviewee 19	Engineering firm	15	
		Interviewee 20	Educational institute	10	
		Interviewee 21	Engineering firm	15	
		Interviewee 22	Educational institute	16	
Fire laboratory	Australia	Interviewee 23	Fire laboratory firm	4	Sections 5, and 8
		Interviewee 24	Fire laboratory firm	13	
		Interviewee 25	Fire laboratory firm	8	
		Interviewee 26	Fire laboratory firm	11	
Fire rescue group	Australia	Interviewee 27	Fire rescue service	6	Sections 3, and 8
		Interviewee 28	Fire rescue service	23	
		Interviewee 29	Fire rescue service	21	
		Interviewee 30	Fire rescue service	37	
		Interviewee 31	Fire rescue service	17	
		Interviewee 32	Fire rescue service	10	
		Interviewee 33	Fire rescue service	20	
Building surveyor	Australia	Interviewee 34	Building surveying firm	9	Section 5
		Interviewee 35	Government department / statutory authority	18	
Manufacturer/Supplier	Australia	Interviewee 36	BIPV supplier	4	Sections 3, 4, and 8
		Interviewee 38	BIPV supplier	13	
		Interviewee 39	BIPV supplier	13	
	Overseas	Interviewee 37	BIPV manufacturer	17	
		Interviewee 40	BIPV manufacturer	18	

Group 1 of the interviewees are experts in the electrical area, who are familiar with the electrical safety or fire safety of PV systems. The purpose of interviews with this group is to confirm the electrical standards, understand what causes the electrical fire hazards of BIPV modules and what measures are applicable to mitigate these hazards. Group 2 are fire safety engineers, who provided suggestions on fire safety strategies in buildings and the evaluation of the fire performance of building elements. They also contributed to understanding fire safety requirements in relevant regulations and standards. International fire engineers contributed to a comparison of the performance and fire test requirements and shared some overseas experiences of BIPV fire safety tests. The contributions from Group 3, fire laboratories, were mainly related to relevant domestic and overseas tests and potential fire hazards of BIPV modules as building elements. Group 4, the fire rescue experts, provided their experiences of how burning BIPV modules threaten the safety of firefighters, especially when BIPV panels continue to operate during fires. Group 5 included experienced building surveyors who contributed to understanding the NCC and Australian standards and expectations of building surveys. The last interview group is BIPV manufacturers and suppliers, who provide a detailed understanding of the features of BIPV modules, the tests they conduct, and the fire hazard mitigation measures they considered in other BIPV projects.

The last column in Table 2.1 presents the corresponding sections in this report that interview results of each group contribute to.

Section 3 BIPV applications and fire hazards

This section provides descriptions of BIPV modules, types of building elements that may integrate or interact with BIPV, and possible fire hazards of BIPV.

3.1 BIPV modules and applications

A BIPV module is the integration of a PV module with an element of a building's construction, designed as a part of, or attached to, the building element. Table 3.1 shows BIPV functions as building elements. A BIPV module is the smallest electrically and mechanically non-divisible PV unit in a BIPV system that retains its building-related functionality. A BIPV system is a PV system in which the PV modules satisfy the above definition of BIPV modules. It includes the electrical components needed to connect the PV modules to external alternative current (AC) or direct current (DC) circuits and the mechanical mounting systems required to integrate the BIPV modules on buildings (Berger et al.2018).

As stated in Section 1, BIPV has dual functions: to generate electricity as part of the energy supply systems to a building, and to replace part of the traditional building envelope. A complete BIPV system includes (Kuhn et al. 2021):

- BIPV modules (thin-film or crystalline, transparent, semi-transparent, or opaque),
- power conversion equipment, comprising an inverter to change the PV's DC output to an AC output,
- possibly additional string diodes between the PV-modules or power optimizers,
- supported and mounted hardware; wiring; safety disconnecting devices; and
- and the constructional integration of the modules into the building envelope.

A BIPV system is a feasible renewable power generation technology to help buildings partially meet their energy consumption load (Debbarma, Sudhakar & Baredar 2017). In addition, a BIPV system has the potential for integration into buildings to supply electricity and improve the energy efficiency of buildings. The installation of BIPV could provide on-site power generation for the supply of electricity to buildings for HVAC systems or water systems (Shukla et al. 2018). Table 3.1 shows BIPV functions in building.

Table 3.1 BIPV functions in building

Relevant building elements	BIPV functions
Wall system	Provides building element (e.g. even if integrated withwall/roof system).
Roof system	
Electricity distribution system	Provide electrical supply for the building
Daylighting system	Transparent BIPV modules installed as daylight apertures, such as skylights and windows, contribute to the adequate lighting provided by daylight
Energy management systems	BIPV modules supply energy to the building and may affect heating and cooling loads.

A typical PV/BIPV module consists of interconnected solar cells encapsulated by a polymer encapsulant and covered on the front by a glass or polymeric front sheet and at the rear by a glass pane, or a polymeric back sheet or back cover made of a unique construction material (IEA PVPS, 2021). Although it is not mandatory, this multi-material composite may be surrounded by a frame providing additional structural support and attachments for mounting. The electrical current produced in the PV active layer is led off via metallic wires/ribbons connected in a junction box installed outside the module. Figures 3.1 shows a typical PV/BIPV module with the different components.

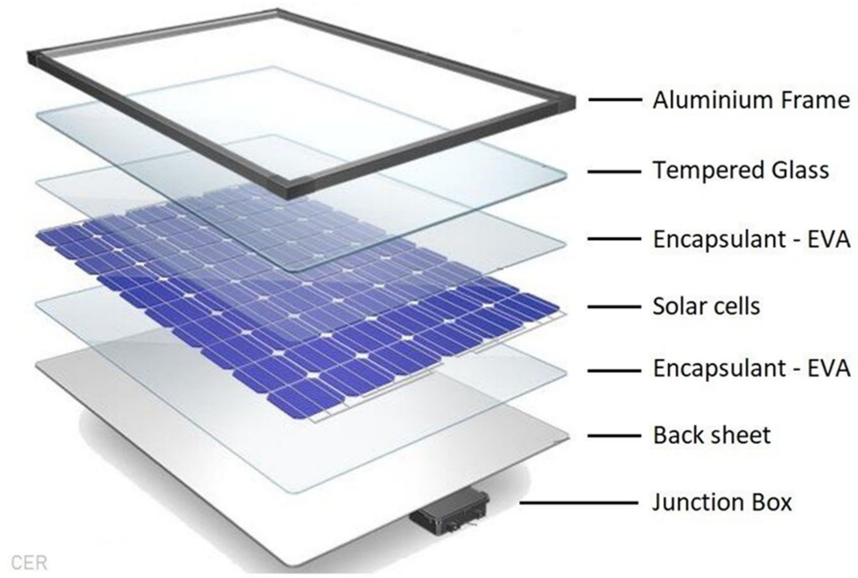


Figure 3.1 PV/BIPV module (IEA PVPS, 2021)

The design of a BIPV module may include modifications from a typical design (shown in Figure 3.2) to improve its performance and integration into buildings. In addition, a PV/BIPV module can be constructed with multiple glazing, where PV laminate is the outer pane of the glazing.

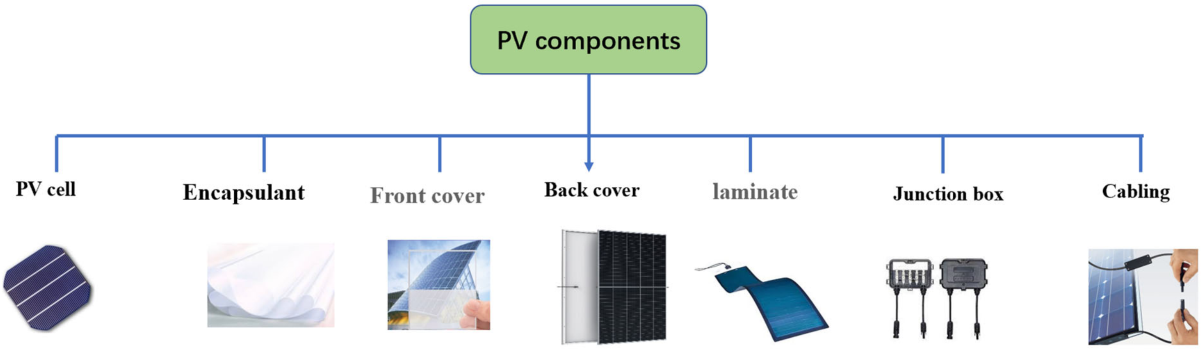


Figure 3.2 PV/BIPV components (IEA PVPS, 2021)

Figure 3.3 shows different building elements that can be integrated with BIPV.

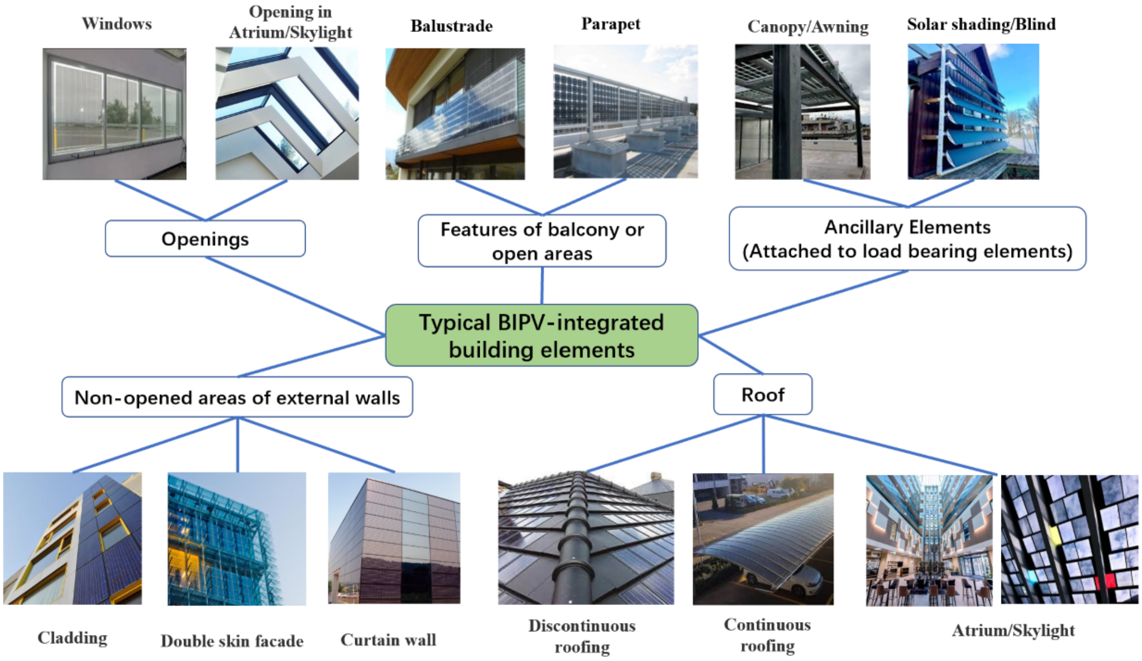


Figure 3.3 Typical BIPV-integrated building elements

Note: 1. A "discontinuous roof" is typically a pitched/sloping opaque envelope consisting of small elements (tiles, slates, shingles, etc.) with the main function of water drainage. A "continuous roof" is a flat or curved roof, characterised by a large uninterrupted layer with the main function of being water-resistant.

2. When BIPV modules are used as ancillary elements, such as awnings, sunshades, canopies, blinds or shading hoods, which are attached to or installed on loadbearing walls, the modules are considered to be part of the loadbearing walls.

According to the IEA's annual report 2020, with the installation in Australia of 4.5GW of additional rooftop and ground-mounted solar panels by the end of 2020, the total installed capacity would reach 20.8GW, putting Australia in the leading position of solar panel per capita at 810W/person. The annual rate of installation has seen a rapid increase from 2018, as shown in Figure 3.4. In 2020, residential solar (0-10kW) grew to over 1.8GW in new installations, while commercial solar (10-100kW) made up a further 1GW [2]. However, few BIPV installations have been made in Australia. Examples of BIPV projects in Victoria are listed in Table 3.2.

[2] This statistic refers to residential solar, but it does not clarify whether this figure includes Class 1 buildings (which are out of the scope of the present study) as well as Class 2 buildings.

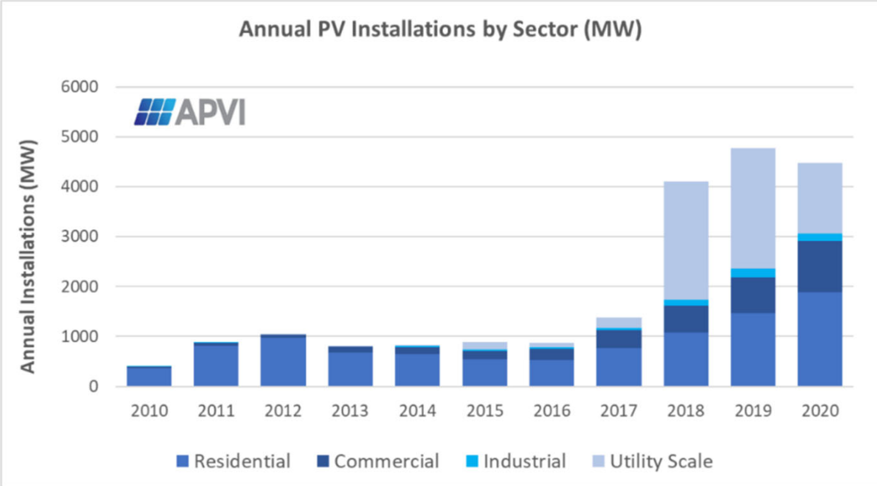
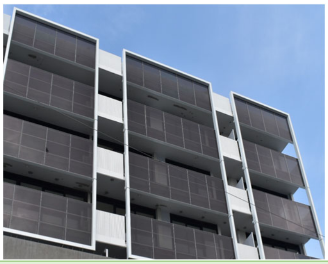


Figure 3.4 Annual PV installations by sector in Australia (IEA annual report, 2020)

Table 3.2 Examples of BIPV projects in Victoria

Building name	Year	Typical BIPV-integrated building elements	Technology	Capacity	Surface area
Paragon Tower (Energy Matters, 2021) 	2021	Cladding	Monocrystalline	42 kW	158 m^2
Melbourne Grammar (Environmental Technology Solutions, 2016) 	2017	Skylight	Amorphous silicon technology (a-si)	1kW	29m^2

Building name	Year	Typical BIPV-integrated building elements	Technology	Capacity	Surface area
Latrobe University (Environmental Technology Solutions, 2016) 	2016	Canopy (bus shelter)	Crystalline silicon (c-si)	28 KW	102 m^2
Northcote - General Apartment (Environmental Technology Solutions, 2016) 	2016	Balustrade	a-si	5 kW	120 m^2
Ballarat (Going Solar, 2007) 	2006	Double skin facade	a-si	8.4 kW	200m^2
University of Melbourne (Snow and Prasad, 2005) 	2002	Curtain wall	c-si	40 kW	-

3.2 BIPV fire hazards[3]

Current academic and industry publications have been reviewed in this project to identify the main causes and mechanisms of BIPV related fires and their impacts: installation, operation, maintenance and rescue.

According to the 2016 report 'Fire Safety of Solar Photovoltaic Systems in Australia' by the Alternative Technology Association (ATA) (as shown in Figure 3.5-3.8), data on PV-related fire incident statistics for four Australian states (NSW, QLD, VIC and WA) were collected by the Australasian Fire and Emergency Services Authorities Council (AFAC). The data show a total of 400 recorded fires involving solar PV arrays and associated equipment from 2009 to 2015 (ATA, 2016). Approximately 40% of the fires recorded from 2009 to 2015 had unknown causes. The next largest percentage cause of PV-related fires was electrical, which is approximately 16%. This electrical category is reported to be caused by components of the solar PV module, e.g., inverter, switchboard, isolators and the like (ATA, 2016). According to the six leading causes of fire in WA, including rooftop DC isolator, other isolator, inverter, other/unknown reasons, solar panels and batteries from 2009 to 2015, it shows that the rooftop DC isolator was the primary cause of fires, with approximately 50% of the recorded fire cases. Fires caused by other isolator and inverters accounted for 16% each, followed by other/unknown causes at 8%. The fires caused by PV panels and batteries were the least common with only 5% each. Detailed information is shown in the following figures. Although the ATA 2016 report did not provide the causes of solar panel-related fires in Victoria, the data in in NSWs and WA still provides insights to illustrate the possible reasons of PV-related fires.

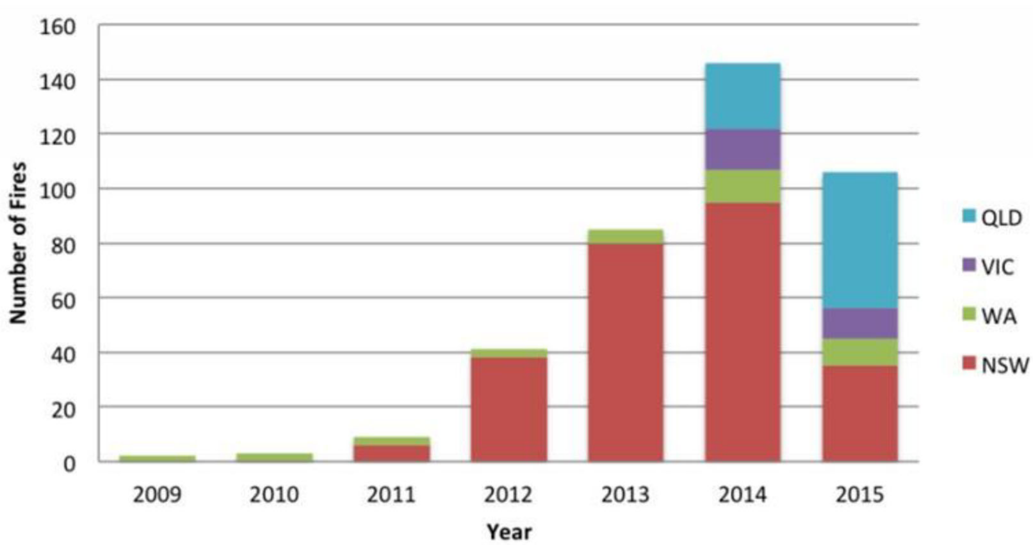


Figure 3.5 PV-related fires in the different Australian states from 2009 to 2015 (ATA, 2016)

[3] Fire hazard is defined in NCC as the danger in terms of potential harm and degree of exposure arising from the start and spread of fire and the smoke and the gases that are thereby generated (NCC 2019).

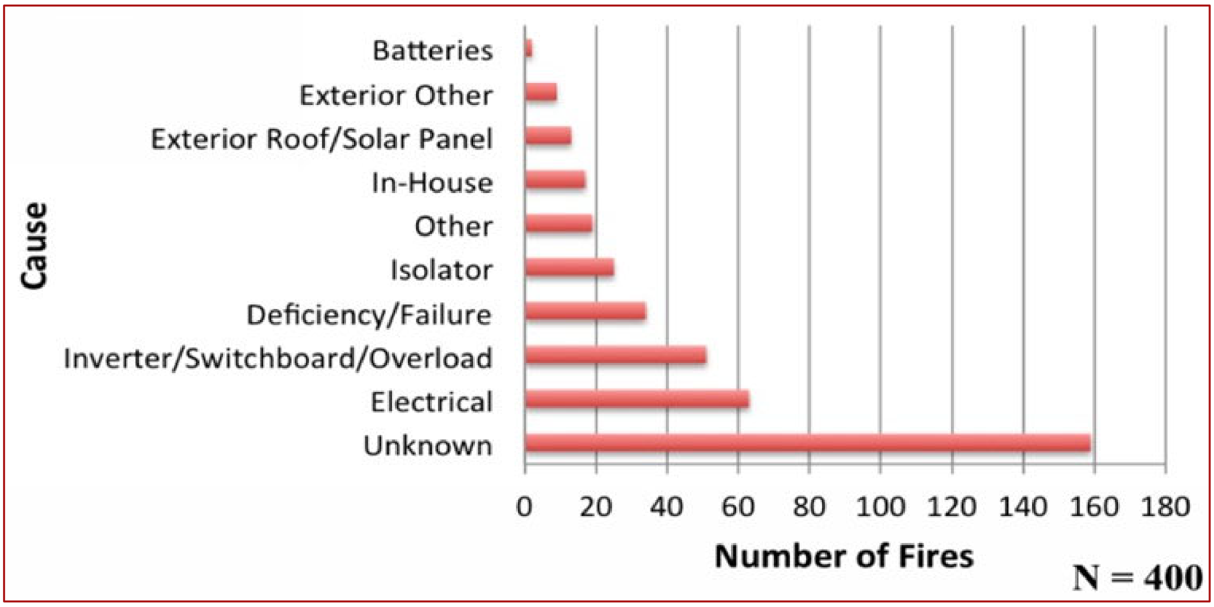


Figure 3.6 Causes of PV-related fires in Australia, 2009 to 2015 (ATA, 2016)

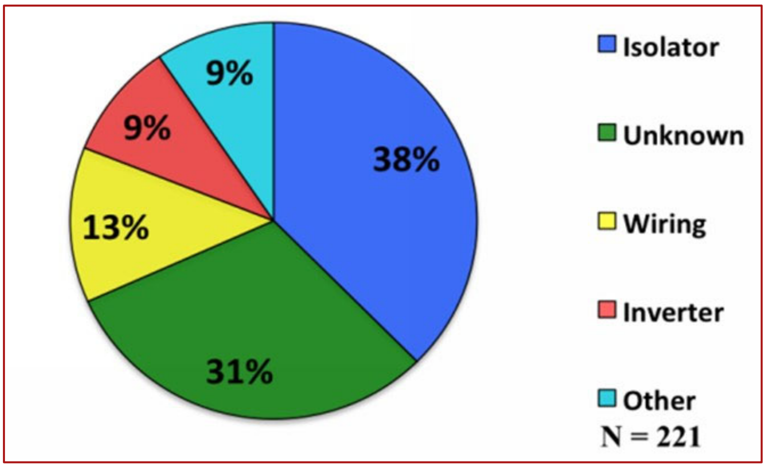


Figure 3.7 Causes of PV-related Fires in New South Wales, 2011 to 2015 (ATA, 2016)

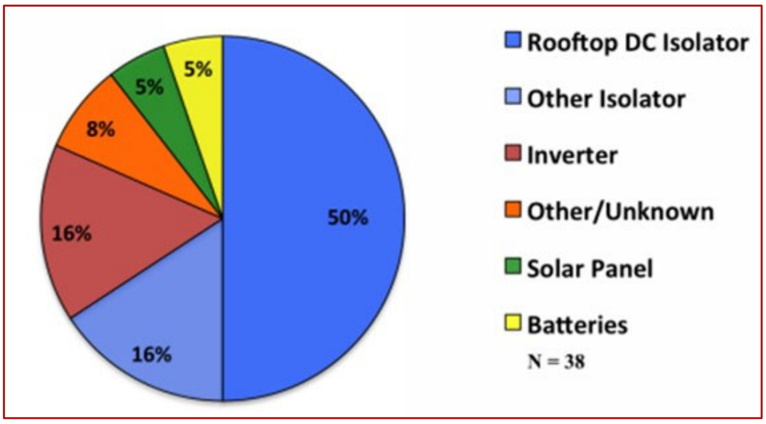


Figure 3.8 Causes of PV-related fires in Western Australia, 2009 to 2015 (ATA, 2016)

Through literature review and interviews, we identify four main fire hazards of BIPV including ignition, fire propagation, potential fire risks to building occupants and fire and rescue personnel, which are discussed in the next few subsections.

3.2.1 Ignition

Ignition has been considered the main BIPV fire hazard which can occur during the processes of installation, operation and maintenance (Sepanski et al. 2018). The the ignition of the PV itself has a high possibility of damaging the entire BIPV module, which means that it is likely to lead to fire involving other parts of BIPV modules (Mazziotti et al. 2016). From another perspective, BIPV modules may also ignite when exposed to a building fire, PV may be ignited by radiant heat exposure if the total heat received exceeds the critical heat flux (Kristensen, Merci and Jomaas 2018). PV modules could be ignited when heat fluxes were higher than 26 kW/m^2 (Yang et al. 2015). The potential fire hazards of ignition likely result from faults in BIPV modules and electrical failures. Hot spots, arcing, and short circuits due to bad connections are the main reasons for the ignition of BIPV modules (Waqar Akram et al. 2022).

PV cells have been found to experience the hot-spot phenomenon due to various faults, including partial shading, material defects, manufacturing errors, and degradation over time (Pandian et al., 2015). Among these reasons, partial shading is a specific fault condition that causes localised hot spots. When a cell, or a group of cells, operates at reverse-bias, it dissipates electricity rather than transferring it, resulting in excessively high temperatures (Dhimish et al. 2018a). Generally, a hot spot is caused by an excessive temperature increase on the surface of the front cover or rear surface which results from a short circuit current (Pandian et al., 2016). Partial shading causes reverse bias in PV cells. The short circuit current is lower than that of other cells in the series string, resulting in an abnormal temperature increase over the damaged cell's surface and the production of a hot spot (Dhimish et al. 2018b). Pandian (2016) states that surface temperature increases beyond 85°C are considered a fire hazard for BIPV modules used in hydrocarbon vapour environments (the environments with rich hydrocarbon vapour/gas such as carbon disulphide, acetaldehyde, and benzaldehyde) since they increase the risk of an explosion caused by the ignition of the hydrocarbon in the atmosphere. Similarly, the increased surface temperature exceeding 230°C is also considered a fire hazard for the coal dust layer when BIPV modules are used in flammable dust environment, such as fibres, coal dust and aluminium. Therefore, partially shaded BIPV modules with a hot spot may ignite a flammable vapour cloud. If the flammable vapour cloud is ignited, it can explode, producing a blast wave, which can cause major destruction over a significant distance (Johnson 2010).

Arcing is another typical cause of ignition (Huang et al. 2017), where a current flows across an air gap by ionising the air. High voltage arcs are extremely hot and can cause the combustion of surrounding materials in less than a second. The reason for this phenomenon could be certain defectives or incorrect installation. Incorrect installation of modules may cause the generation of sufficient heat energy to start an arc fault which may then cause a fire (Chen et al., 2019). Furthermore, a poor connection that is not tight and has low resistance is one of the main reasons for overheating, which is likely to trigger the high temperature of electrical components (Cancelliere 2016). For example, the connectors between BIPV modules and the connections to the wiring of the entire BIPV system may have a bad electrical connection, like a small gap, which can cause DC arcing. When the arc is exposed to the sunlight, it may become a significant ignition source. Bypass diodes, important components in PV systems, are very likely to cause arc faults. It takes less than 0.1 seconds for the polymeric back sheet and the polymer materials in the area adjacent to the diode and junction box to ignite (Johnson, Bower and Quintana 2012). Moreover, the build-up of contaminants (e.g., oxide) on electrical contacts can cause resistive heating, resulting in the breakdown of materials and subsequent arcing (Witter n.d.). PV components can be ignited by electrical arcing, which is likely to cause a potential hazard to occupants due to fire.

3.2.2 Fire propagation

Another potential hazard of BIPV is fire spread since BIPV modules contain combustible materials (Yin, Jiang and Qiu, 2018). Polyethylene-co-vinyl acetate (EVA) and Polyvinyl butyral (PVB) are the main materials used as BIPV encapsulants. Both EVA and PVB are combustible. According to Glass for Europe (2015), the calorific value of PVB and EVA are 30 MJ/kg and 40 MJ/kg, respectively. Although the layer of EVA or PVB is relatively thin in BIPV panels, of the order of 0.7 mm to 1.0 mm, it burns readily in fire. The spread of fire and smoke from the BIPV modules may affect the fire safety of an entire building (Aram et al. 2021), because the BIPV modules may facilitate rapid fire spread from the point of ignition to other parts of the building. According to recent research, both the mounting type and the location of BIPV modules affect fire propagation (Miao & Chow 2019). Fire spread can occur in four pathways: 1) spread upwards via the façade (e.g., cavities, the chimney effect) or other pathways; 2) spread downwards via façade or flaming debris; 3) spread to other floors; 4) spread to adjacent buildings, typically by radiation.

Compared with mounting on the roof, BIPV modules installed on vertical façades are considered a greater fire hazard (Ju et al., 2017). According to the results of PV panel burning tests, the burning behaviour of BIPV/PV panels is determined by the backsheets of the panels (Mazziotti et al., 2016). In other words, the combustible material used on the backsheet is likely to lead to severe burning of a BIPV module. Chow, Han and Ni (2017) identified the high likelihood of ignition of a BIPV panel when it is exposed to a heat flux of over 35 kW/m^2. Furthermore, if there exists a vertical cavity between BIPV modules and other components of the external wall, BIPV modules can spread flames and smoke to upper parts of the façade via this cavity and consequently to other areas of the building such as indoor space and horizontal BIPV-integrated roofs (Miao and Chow, 2019).

When a fire breaks out on PV or BIPV panels installed in a roof, the fire spread over the roof can be accelerated in windy conditions. When ignited, the burning PV or BIPV product may drip onto its surface or onto another combustible PV or BIPV beneath it, causing a secondary fire (Kristensen, Faudzi and Jomaas, 2020). PV systems are capable of generating power at voltages ranging from 600 to 1500 volts. Even at low current, this high range of DC voltage is dangerous to firefighters (Nair 2018). If BIPV modules are connected on the façade of multiple single occupancy units (SOUs), their ignition can lead to the fire spread to different SOUs and floors. For example, when BIPV modules are integrated in a curtain wall continuously between floors, the fire can spread to multiple floors due to the heating and opening at the joint connection between curtain wall and floor slabs (Ku et al. 2022).

BIPV associated fires can also be spread to adjacent buildings. Cheng, H (2011) presented that the fire spread between buildings can occur when the adjacent building received higher value of radiation heat flux than the ignition heat flux of combustible materials on the adjacent building. The experiment conducted by Carlsson, E (1999) stated that the adjoining façade had higher possibility to be ignited when the value of radiation changed from 12.5 kW/m^2 to 18 kW/m^2. Therefore, the combustible nature of different components in BIPV modules can increase the radiative heat flux of associated fires to a critical level that can cause fire spread to an adjacent building.

At the same time, fire from the internal area can potentially reach BIPV and ignite the module. For example, BIPV windows or BIPV curtain walls are directly connected to indoor areas causing BIPV modules to easily catch fire from an internal fire source. Flashover is a fire phenomenon that may occur indoors, which is defined as the near-simultaneous ignition of most of the directly exposed combustible material in an enclosed area (McCaffrey et al. 1981). This phenomenon occurs when the radiant heat flux from the hot smoke layer is high enough to ignite the flammable vapour from the materials undergoing pyrolysis. The development of flashover generally occurs between the stages of growth and fully-developed fire (Graham, Makhviladze and Roberts, 1995). BIPV modules tend to be ignited by the flashover from adjacent fire rooms (Ju et al., 2017 For instance, Huang et al. (2018) reported that the flashover was observed in the fire chamber at the 4th minute, where BIPV-integrated walls were tested in accordance with ISO 834-1, CNS 14803 and ISO 3008, and the furnace temperature reached 500°C when the flashover occurred. Severe glass breakage of BIPV modules was also observed during the test. The possibility of flashover for indoor fires involving PV panels ranges from intermediate to high, depending on the material of the panel and its heat flux capacity (Yang et al., 2015; Yin, Jiang and Qiu, 2018).

3.2.3 Potential hazards to building occupants

The installation, operation and maintenance of BIPV modules on buildings present various potential hazards to building occupants.

In relation to the safety of building occupants, three primary factors may be relevant: impact on evacuation, falling debris and toxic gas emissions.

As stated previously, the burning behaviour of BIPV modules can cause flame spread and smoke development in indoor areas, which may generate the safety concern for building occupants. Fire propagation via BIPV modules connecting different SOUs may create a pathway for fire and smoke spread to multiple SOUs and potentially into evacuation paths such as corridors and exit stairways.

If a fire occurs in BIPV modules, the collapse of the panels or falling debris from burning BIPV modules may threatens the safety of evacuees when exiting the building/firefighters in operation and may trigger the ignition of other building elements on lower floors. For example, Cancelliere (2016) stated that falling debris from BIPV panels would undoubtedly be considered a potential hazard for occupants and firefighters in fire incidents caused by BIPV panels. Previous research has demonstrated that the burning of BIPV modules can cause structural breakage of panels (Huang et al., 2018; Miao and Chow, 2019). Especially for non-glass back sheet panels, compared with glass-glass construction, it is much easier to generate falling debris. According to an experiment conducted by Despinasse and Krueger (2015), a glass/plastic structure panel develops burning debris that falls in a few minutes, which is faster than a glass/glass structure solar panel. Although current BIPV modules use toughened glass, which means the modules may not disintegrate easily, the mass of all debris is still of concern.

While flame spread has been recognised as one of the crucial fire hazards of BIPV modules, the underestimation of toxic smoke emitted from BIPV-associated fires may lead to catastrophic results. However, to date no test method exists to evaluate toxic gas generation and development from burning BIPV modules. Liao et al.(2020) tested polyethylene terephthalate (PET) laminated PV panels and observed various types of toxic gas generated, including hydrogen fluoride, hydrogen cyanide and volatile organic compounds (VOCs), and, more importantly, the high concentration of sulphur dioxide. Moreover, a type of PV cell named Cadmium telluride (CdTe), which is a potentially toxic material. The way it is encapsulated in glass in BIPV pannels significantly affects the possibility of inhalation or ingestion. Freeing the CdTe from the laminate after burning is challenging. Potential exposure to Cd vapour via inhalation may occur even with residential fires (Bohland et al.2000).

3.2.4 Potential hazards to fire and rescue personnel

In relation to the safety of firefighters, electric shock is the main potential fire hazard during firefighting operations (Yang et al. 2015), though the hazards identified for occupants in the previous section are also relevant. If the fire brigade employs water-based extinguishing agents to fight firewhile BIPV modules are active, the firefighters could receive electric shocks (Tommasini et al., 2014). Therefore, firefighters are likely to face the potential hazard of electric shock at the sites of fires. An additional point is the role of residual electricity in potential fire development and spread. During a fire event, the panels themselves may continue to produce electricity when exposed to light under a wide variety of light conditions. Even when a fire occurs, the BIPV panels may still operate as long as there is sunlight. Therefore, the connection between the panels and the inverter-isolating switch remains live.

The potential fire hazards associated with BIPV are summarised in Table 3.3.

Table 3.3 Causes of BIPV/PV fire hazards

Possible consequences of hazards	Cause of fire hazards	Description
Ignition	BIPV combustibility	The encapsulating materials of BIPV modules are combustible, affecting their fire performance (Mazziotti et al., 2016).
	Ignitibility	Faulty BIPV modules and related electrical issues such as hot-spots, arcing, and incorrect connections which cause short circuits are the major cause of BIPV ignition (Kristensen, Merci and Jomaas, 2018).
		Internal building fires may expose panels to radiant heat, causing ignition of BIPV modules.

Possible consequences of hazards	Cause of fire hazards	Description
Propagation	Fire propagation	Compared with mounting on roofs, BIPV modules installed on vertical façades may be a more significant fire hazard (Ju et al., 2017). They may cause secondary fires (Kristensen, Faudzi and Jomaas, 2020) and spread flame and smoke to other parts of buildings (Miao and Chow, 2019).
Hazard to building occupants	Evacuation	The spread of fire and the production of smoke may reduce the available evacuation time due to fire propagation between fire compartments.
	Falling debris	Falling debris from burning BIPV panels is dangerous for building occupants and firefighters (Cancelliere and Liciotti, 2016).
	Toxic gas emissions	Toxic gases from burning PV modules can cause harm to people inside the building (Bohland et al.2000).
Hazard to fire rescue groups	Electric shock	When fire occurs in a building where a BIPV system is in operation, electrical fires cannot be completely prevented by cutting the building's circuit, posing the hazard of electric shock to fire-fighters (Chow, Han & Ni 2017).

3.3 Section summary

BIPV fire hazards include ignition due to hot spots, arcing, and installation error, fire propagation, and hazards to rescue operations related to electric shock and toxic gas emissions. The fire mechanisms associated with BIPV which affect the fire safety of buildings are:

- ignition and burning of BIPV components,
- fire spread to openings or through roofs and external building surfaces,
- fire spread from internal areas to BIPV components and vice versa,
- prevention of safe evacuation from buildings or safe access for fire brigade.

The next three sections provide an overview of the regulatory landscape and the relevant requirements for BIPV fire safety.

Section 4 Regulatory landscape in Victoria

The fire safety of renewable energy sources, especially solar energy, has begun to be regarded as an important topic by many scholars from technical, legal, and policy perspectives all over the world (Shen et al. 2021). The increasing use of BIPVs in the modern era does not necessarily correspond to the relevant legislative measures, particularly those addressing the relationship between BIPV systems, the built environment, and fire safety (Kapetanakis, Kolokotsa & Maria 2014). The increase of BIPV projects in Australia in recent years raises considerable concerns, especially related to the fire safety of BIPV modules installed as part of or the whole building elements. This section provides an overview of the current regulatory landscape of both building and electrical aspects applicable to BIPV fire safety (Figure 4.1). Only Victorian references are considered in this report, but other jurisdictions have similar legislation and regulations.

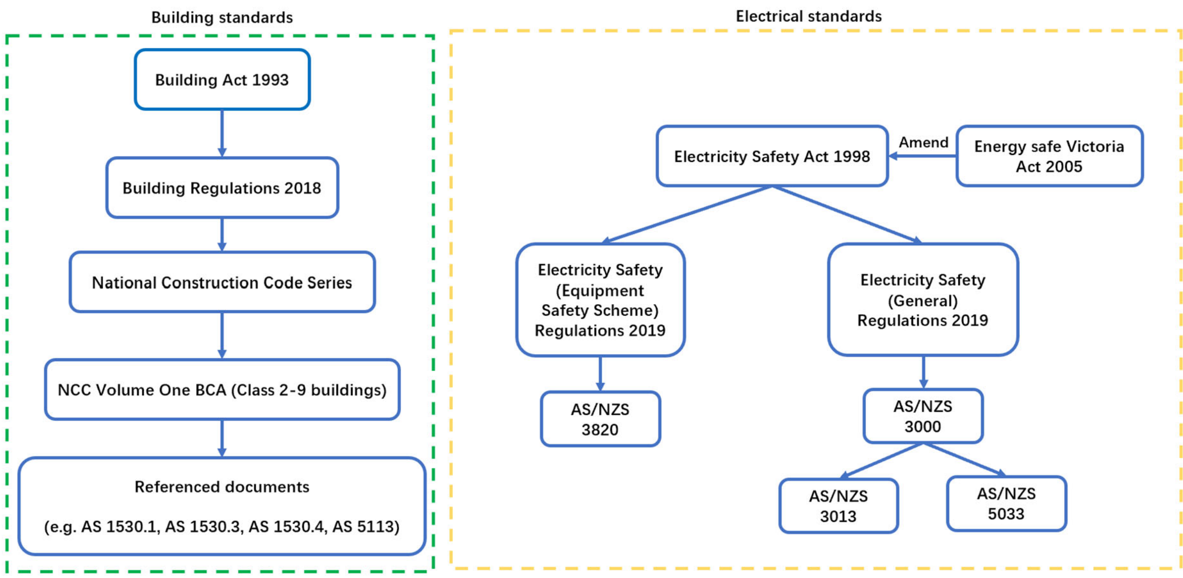


Figure 4.1 Regulatory landscape applicable to BIPV fire safety

4.1 Building regulatory landscape applicable to BIPV fire safety

In Victoria, the Building Act 1993 is to, amongst other things:

(a) regulate building work and building standards;

(b) provide for the accreditation of building products, construction methods, building components and building systems; and

(c) provide an efficient and effective system for issuing building and occupancy permits and administering and enforcing related building and safety matters and resolving building disputes.

The Act provides the power that the Governor in Council may make regulations for or with respect to prohibiting or regulating:

(a) the construction, use, maintenance, demolition and removal of buildings;

(b) any matter relating to the safety of buildings and places of public entertainment; and

(c) the use and maintenance of places of public entertainment.

The Victorian Building Authority (VBA) was established under the Building Act 1993 and is subject to the direction and control of the Minister, where those directions may be general or specific. The VBA regulates Victoria's building and plumbing industries.

The Building Regulations (2018), which deals with administrative matters and came into effect on 2 June 2018, have the following objectives that are relevant to the research in this document:

(a) to remake with amendments the regulations which control the design, construction and use of buildings and places of public entertainment; and

(b) to prescribe standards for the construction and demolition of buildings; and

(c) to prescribe standards of safety for places of public entertainment; and

(d) to regulate matters relating to the use and maintenance of buildings and places of public entertainment; and

(e) to prescribe standards and matters relating to the maintenance of fire safety and safety measures.

The Building Code of Australia (BCA), which deals with technical matters, is adopted by and forms part of the Building Regulations as modified by the Regulations. Since 2012, the BCA for class 2 to 9 buildings as well as for class 1 buildings are combined with the Plumbing Code to form the National Construction Code series, with volume one being the BCA for class 2 to 9 buildings, volume two being the BCA for class 1 buildings, and volume three being the Plumbing Code. In this research, only NCC 2019 volume one, hereinafter referred to as the NCC, which relates to Class 2 to 9 buildings is taken into consideration.

In Australia, whether a PV product is to be attached to a building element, or part of a building element, or form a building element by its own-self, it needs to comply with the NCC.

Compliance with the NCC is achieved by complying with the Governing Requirements of the NCC and the Performance Requirements.

Compliance with Performance Requirements can be satisfied by formulating a Performance Solution, adopting a Deemed-to-Satisfy Solution, or a combination of a Performance Solution and a Deemed-to-Satisfy Solution.

Further details on which Performance Requirements are relevant and how compliance with Performance Requirements can be achieved are provided in section 5 of this report.

4.2 Electrical regulatory landscape applicable to BIPV fire safety

Electrical regulation is divided across 3 distinct areas (generation/distribution, equipment safety, installation safety). Generation/distribution is covered by the Electricity Industry Act while equipment safety and installation safety are covered under the Electricity Safety Act. As this report only focuses on the safety area of electrical regulation, Electricity Safety Act 1998 and the regulations under it are considered in relation to BIPV fire safety.

The Electricity Safety Act 1998 (Authorised Version incorporating amendments as of 1st January 2021) makes further provisions relating to:

(a) the safety of electricity supplyand use, and

(b) the reliability and security of electricity supply, and

(c) the efficiency of electrical equipment.

Energy Safe Victoria Act 2005 makes consequential amendments to the Electricity Safety Act 1998 and establishes Energy Safe Victoria (ESV) as the safety regulator for Victoria for electricity and gas. This Act aims to:

(a) establish Energy Safe Victoria; and

(b) abolish the Office of the Chief Electrical Inspector; and

(c) make consequential amendments to the Electricity Safety Act 1998 and other Acts.

The Electricity Safety (Equipment Safety Scheme) Regulations 2019 were made on 19 March 2019 under sections 153 and 157 of the Electricity Safety Act 1998. The objective of these regulations is for the purposes of the Electricity Safety Act 1998:

(a) to prescribe standards for electrical equipment and relevant standards for in-scope electrical equipment; and

(b) to provide for the variation, renewal and transfer of certificates of suitability and certificates of conformity; and

(c) to prescribe the marking of electrical equipment.

As stated in the Electricity Safety (Equipment Safety Scheme) Regulations 2019, for the purposes of section 54 for equipment that is not in-scope and s67A for equipment that is level 1 in-scope of the Act 1998, the prescribed standard for both of these equipment classes is AS/NZS 3820 (Essential safety requirements for electrical equipment). AS/NZS 3820 sets out general requirements for electrical equipment, to ensure that electrical equipment is constructed in accordance with good engineering practice in regard to safety such that it does not endanger the safety of persons.

The Electricity Safety (General) Regulations 2019 became law on 6th December 2019, is made under sections 149, 151, 151A, 152 and 157 of the Electricity Safety Act 1998. This regulation generally

(a) to prescribe the methods to be followed in carrying out electrical installation work, and

(b) to prescribe the quality of materials, fittings and apparatus to be used in connection with electrical installations; and

(c) to provide for the inspection of prescribed electrical installation work; and

(d) to provide for the testing and certification of electrical installation work; and

(e) to prescribe standards for the design, construction, operation and maintenance of electrical installations, and

(f) to provide for the protection of persons from risk, and property from damage, associated with the generation, transmission, distribution and use of electricity.

Australian standards AS/NZS 3000 (Electrical Installations) is called up in the Electricity Safety (General) Regulations 2019, as published or amended from time to time. AS/NZS 3000 was prepared by the Standards Australia/Standards New Zealand Committee EL-001. It is also known as the wiring rules. AS/NZS 3013 (Electrical installations—Classification of the fire and mechanical performance of wiring system elements), and AS/NZS 5033 (Installation and safety requirements of photovoltaic arrays) are referenced in AS/NZS 3000. AS/NZS 3013 (also known as Special Wiring Systems) was prepared by the Standards Australia/Standards New Zealand Committee EL-037 on Special Wiring Systems to supplement AS/NZS 3000. This Standard provides a system of classification of the degree of protection inherent in wiring system elements against accidental mechanical damage and under fire conditions for specified periods. AS/NZS 3000 refers to AS/NZS 5033 regarding the requirements of PV. AS/NZS 5033 sets out general installation and safety requirements for electrical installations of PV arrays, including DC array wiring, electrical protection devices, switching and earthing provisions. The requirements in these national standards relevant to the fire safety of BIPV are described in Section 6.

As a specific type of PVs, BIPVs should also comply with the current requirements for electrical safety and existing PV standards which affect fire safety of buildings in Victoria. Also, the installation standard has a gap in regard to BIPV. The focus of the development of the standard was for traditional PV installation and therefore the installation practices outlined in this standard may be deficient for BIPV.

4.3 Section summary

An overview of the existing regulatory landscape from both building and electrical aspects relevant to BIPV fire safety is provided in this section. As NCC is a principal and fundamental technical document in Australia, Section 5 focuses on the requirements in the NCC, Volume 1. AS/NZS 3000, AS/NZS 3013, and AS/NZS 5033 are reviewed in Section 6 from the electrical aspect.

Section 5 Relevant fire resistance and combustibility requirements in NCC

Since PV modules need to be exposed to sunlight for them to function, it is evident that PV modules would have to be installed on the outside of buildings where sunlight can reach, which includes roofs, external walls, balconies and terraces. The associated building elements include, for example, windows in external walls, as well as balustrades and parapets for balconies and terraces.

The PV modules can be applied as an attachment to the building elements identified above, or as a part of or wholly the building elements. However, the NCC requirements for these two applications differ.

The sections in the NCC that contain fire safety requirements include:

- Section C – fire resistance
- Section D – access and egress
- Section E – services and equipment
- Part G3 – atrium construction
- Part G5 – construction in bushfire prone areas, and
- Section H – special use buildings.

This research focusses only on the fire resistance and combustibility requirementsin Section C of the NCC for external walls and skylights.

Requirements for use of BIPV as spandrels, window elements, roofs, and atrium construction (eg atrium roofs) are not discussed. These will require separate examination.

5.1 Fire safety requirements in NCC Section C for attachments to building elements

When a PV module is attached to a building element, then the PV module is considered to be an ancillary element. The relevant Deemed-to-Satisfy (DtS) Provision is clause C1.14 which states the following.

C1.14 Ancillary elements

An ancillary element must not be fixed, installed or attached to the internal parts or external face of an external wall that is required to be non-combustible unless it is one of the following:

(a) An ancillary element that is non-combustible.

(b) A gutter, downpipe or other plumbing fixture or fitting.

(c) A flashing.

(d) A grate or grille not more than 2 m^2 in area associated with a building service.

(e) An electrical switch, socket-outlet, cover plate or the like.

(f) A light fitting.

(g) A required sign.

(h) A sign other than one provided under (a) or (g) that—

- *(i) achieves a group number of 1 or 2; and*
- *(ii) does not extend beyond one storey; and*
- *(iii) does not extend beyond one fire compartment; and*
- *(iv) is separated vertically from other signs permitted under (h) by at least 2 storeys.*

(i) An awning, sunshade, canopy, blind or shading hood other than one provided under (a) that—

- *(i) meets the relevant requirements of Table 4 of Specification C1.10 as for an internal element; and*
- *(ii) serves a storey—*
  - *(A) at ground level; or*
  - *(B) immediately above a storey at ground level; and*
- *(iii) does not serve an exit, where it would render the exits unusable in a fire.*

(j) A part of a security, intercom or announcement system.

(k) Wiring.

(l) A paint, lacquer or a similar finish.

(m) A gasket, caulking, sealant or adhesive directly associated with (a) to (k).

For PV modules as an attachment to a building element, the sub-clauses C1.14(a) and (i) are relevant.

In order to satisfy the requirement in C1.14(a), every component of the PV module needs to achieve a result of "not deemed combustible" when tested to AS 1530.1 'Combustibility test for materials'.

To satisfy the requirement in C1.14(i), the PV module needs to be tested to AS 5637.1 'Determination of Fire Hazard Properties - Wall and Ceiling Linings' that demonstrates the test specimen achieves a material group number of 1, 2 or 3, a smoke growth rate index not more than 100 or an average specific extinction area less than 250 m^2/kg.

Another relevant DtS Provision is clause 2.4 of Specification C1.1 of the NCC, which states that the method of attaching or installing a finish, lining, ancillary element or service installation to the building element must not reduce the fire-resistance of that element to below that required. This would need a fire engineering analysis that considers the fire-resistance of the element as stated in the fire resistance test report as well as the method of attachment.

An alternative pathway to comply with the NCC is to formulate a Performance Solution, by a fire safety engineer, to justify that the proposed PV modules as an attachment to a building element complies with the Performance Requirements that are relevant to the project/building:

- CP2 Spread of fire
- CP3 Spread of fire and smoke in health and residential care buildings
- CP4 Safe conditions for evacuation

In order to support the formulation of a Performance Solution, engineering data including the propensity of ignition, the extent of fire spread, the rate of flame spread, toxic species production rate, and the concentrations of the toxic species in the smoke after the PV module is ignited will need to be available.

On the propensity of ignition and extent of fire spread, an AS 1530.3 'Methods for fire test on building materials, components and structure Part 3: Simultaneous determination of ignitability, flame propagation, heat release and smoke release' test can be carried out with the test data reverse engineered to crudely determine the minimum radiant heat flux to cause piloted ignition and the extent of fire spread.

On the rate of flame spread, there is currently not an existing Australian Standard available to provide such data. The alternative is to employ the American ASTM Standard E1321 'Standard Test Method for Determining Material Ignition and Flame Spread Properties'.

With respect to toxic species production rate and concentration of the toxic species in the smoke, there is currently not an existing Australian Standard available to provide such data. Whilst the AS 5637.1 test results could be used to derive a smoke growth rate index or an average specific extinction area, and the AS 1530.3 test results could be used to derive a smoke release index, the two tests only measure the visible particles in the smoke and not the other combustion products. There are overseas standards on testing the toxicity of fire effluents, such as ISO 19702, ASTM E1678, NFPA 269, and NFX70-100.

However, it is known in the fire engineering fraternity that for internal enclosures, it is often the reduction of visibility of the smoke layer that first triggers the onset of untenable conditions. It may be acceptable to the regulatory authority that the raw data from the AS 5637.1 or the AS 1530.3 test on visible particle production rate and concentration is used a surrogate to evaluate the toxicity aspect.

Where there are many PV modules attached to a building element and arranged in a configuration that there could be potential fire spread between two or multiple floors via the PV modules, an AS 5113 'Fire propagation testing and classification of external walls of buildings' test may need to be carried out to demonstrate that the PV modules do not facilitate fire spread, or to provide engineering data for a fire safety engineer to evaluate and justify that fire spread is not expected with respect to the specific project details.

5.2 Fire safety requirements in NCC Section C for PV modules to be part of a building element or to be wholly a building element

When the PV modules forms part of a building element or wholly as a building element itself, the DtS Provisions and Performance Requirements that correspond to the building element apply.

As stated above, the likely building elements involved would be roofs, external walls, balconies and terraces. Note that for the purpose of this report, the term ‘external wall’ is limited to an external wall integrated with BIPV, curtain walls, double skin façades, claddings, and spandrels, as well as BIPV ancillary elements, such as canopies/awnings and solar shadings/blinds which make up the assembly of the external wall.

Roofs are required to have a fire-resistance level (FRL) only in buildings of type A construction per NCC specification C1.1 Table 3. The FRL required depends on the occupancy classification. When a BIPV module also forms and functions as a roof, it needs to demonstrate that the BIPV module achieves the same FRL as the roof by testing the module to AS 1530.4 ‘Fire-resistance test for elements of construction’. An alternative pathway to comply with this NCC requirement is to formulate a Performance Solution, by a fire safety engineer, which demonstrates that the Performance Requirements CP1 and CP2 are met.

When a BIPV serves as a roof light, the NCC DtS clause C1.10 and Specification C1.10 are appliable and the BIPV needs to meet the requirements for ceilings in Table 3 of Specification C1.10 with respect to material group number, when tested to AS 5637.1. If the building is not fitted with a sprinkler system (other than a FPAA101D or FPAA101H system) complying with the NCC Specification E1.5 then the BIPV module is required to have a smoke growth rate index not more than 100; or an average specific extinction area less than 250 m^2/kg, when tested to AS 5637.1. An alternative pathway to comply withthis NCC requirement is to formulate a Performance Solution, by a fire safety engineer, which demonstrates that the Performance Requirements CP2 and CP4 are met.

With respect to external walls integrated with BIPV, i.e., the PV module forms part or as a whole of the external wall, this report considers conventional external walls, curtain walls, and double skin facades.

Conventional external walls, for the purpose of this report, refer to external walls constructed with concrete, masonry, or lightweight construction, but not substantially glass. NCC clause C1.9 states that in a building required to be of Type A or B construction, the external walls, including all components incorporated in them including the facade covering, framing and insulation, must be non-combustible. The BIPV that forms part of wholly of the external wall will therefore also need to be non-combustible, when tested to AS 1530.1. An alternative pathway to comply with this NCC requirement is to formulate a Performance Solution, by a fire safety engineer, which demonstrates that the Performance Requirement CP2 is met. Depending on the amount, location and configuration of the BIPV modules, the Performance Solution may be justified by a qualitative analysis, a quantitative analysis using hand calculation, a quantitative analysis using computational fluid dynamics (CFD) techniques, or a test to AS 5113.

According to Tables 3 to 5 of Specification C1.1 of the NCC, external walls may require to achieve an FRL, depending on the separation distance between the external wall and the fire-source feature [4]. The BIPV that forms part or wholly of the external wall will therefore also need to achieve an FRL, when tested to AS 1530.4. An alternative pathway to comply with this NCC requirement is to formulate a Performance Solution, by a fire safety engineer, which demonstrates that the Performance Requirements CP1 and CP2 are met. This Performance Solution needs to be considered on a case by case basis.

For curtain walls [5], clause 2.5 of Specification C1.1 of the NCC states that they need not have an FRL if they are of non-combustible construction and fully protected by automatic external wall-wetting sprinklers. Therefore, if the BIPV that forms part or wholly of the curtain wall does not attain a 'deemed non-combustible' result when tested to AS 1530.1, then the BIPV curtain wall need to be tested to AS 1530.4 to demonstrate its FRL. An alternative pathway to comply with this NCC requirement is to formulate a Performance Solution, by a fire safety engineer, which demonstrates that the Performance Requirement CP2 is met. This Performance Solution needs to be considered on a case by case basis. In some instances, a test to AS 5113 may be required to provide the necessary data to support the Performance Solution with respect to fire spread via the wall Other fire safety aspects, including the lack of full fire separation between the floor levels at the floor-wall junctions due to the curtain walls may also need to be addressed, Similar requirements may also apply for at the junctions of the curtain wall and internal walls if the internal walls are required to be fire resistive.

With respect to double skin facades where the BIPV forms part or wholly of them, the fundamental hazard is that the gap between the inner skin and the outer skin could facilitate fire and smoke spread from one floor to multiple floors, even without the BIPV. The NCC does not have any DtS Provisions for double skin facades. Therefore, the only pathway to comply with the NCC is to formulate a Performance Solution, by a fire safety engineer, which demonstrates that the Performance Requirements CP2 and CP4 are met. The Performance Solution would likely need to be justified by a quantitative fire engineering analysis using CFD techniques, and a test to AS 5113 with modification to the test specimen configuration (this is due to the fact that AS 5113 is not applicable to double skin façade) may be required to generate engineering data to support the CFD simulation(s). Other fire safety aspects, including the lack of full fire separation between the floor levels created by the wall cavity must also be addressed. Similar requirements may also apply for at the junctions of the facade and internal walls if the internal walls are required to be fire resistive.

With regard to balconies and terraces, the BIPV would likely to be on the vertical side of the balustrades or the parapets for the balconies and terraces only. There are no fire safety related NCC DtS Provisions that relate to balustrades and parapets. However, the Performance Requirements CP2 and CP4 would be relevant. Parameters that may need to be considered include the propensity of ignition, the flame height, toxic species production rate, and the concentrations of the toxic species in the smoke after the BIPV is ignited.

Refer to section 5.1 above for discussions on propensity of ignition, toxic species production rate and concentrations of the toxic species could be determined.

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[4] Fire-source feature means—
   (a) the far boundary of a road, river, lake or the like adjoining the allotment; or
   (b) a side or rear boundary of the allotment; or
   (c) an external wall of another building on the allotment which is not a Class 10 building.

[5] Curtain wall means a non-loadbearing external wall that is not a panel wall.

With respect to flame height from a burning BIPV on a vertical orientation, there are currently no Australian Standards for obtaining such data. A test carried out to ASTM Standard E1321 may be an avenue, where the flame height during the test is observed and measured to generate the baseline data for further fire engineering analysis by a fire safety engineer.

5.3 Section summary

The fire resistive and combustibility requirements in the NCC on PV modules that are attached to external walls differ from PV modules that form part of wholly the external walls. This section has provided an overview of the different requirements in the Deemed-to-Satisfy Provisions of the NCC as well as alternative pathways, that is, formulating a Performance Solution, to demonstrate compliance with the relevant NCC Performance Requirements.

Section 6 Relevant electrical requirements in Victorian legislation

As building elements, some of the fire performance requirements of BIPV are presented in Section 5 with reference to selected provisions of Section C of the NCC Volume 1. In addition, as electrical products, the relevant electrical requirements of BIPV are reviewed in this section. This section refers only to the relevant electrical requirements in the standards related to BIPV modules. It does not include the requirements for other electrical elements such as inverters, batteries, etc., or the entire electrical systems.

Section 6.1 presents the electrical requirements relevant to BIPV fire safety. Section 6.2 provides the relevant tests for the standards or legislation referred to in Section 6.1.

6.1 Relevant regulations and legislation

Table 6.1 presents the minimum electrical requirements applicable to BIPV electrical fire safety. The first five regulations in the table regulate the industry but not specific systems. Therefore, more attention should be given to the system-based requirements including Australian Standards: AS/NZS 3013 (Electrical installations—Classification of the fire and mechanical performance of wiring system elements) and AS/NZS 3000 (Electrical installation).

Table 6.1 Electrical requirements relevant to BIPV fire safety in standards referred to in NCC (Victoria only)

<table>
<tr><th colspan="2">Regulation/ legislation</th><th>BIPV electrical requirements</th><th>Clause/ secondary referenced standards</th></tr>
<tr><td rowspan="5">Industry legislation and regulations</td><td rowspan="2">Electricity Safety Act 1998</td><td>Electrical equipment</td><td>Part 4 – Electrical equipment</td></tr>
<tr><td>Fire hazard rating</td><td>Part 8—Bushfire mitigation requirements for certain operators and electric line clearance</td></tr>
<tr><td rowspan="2">Electricity Safety (General) Regulations 2019</td><td rowspan="2">Installation requirements</td><td>Division 1— Wiring methods for electrical installations</td></tr>
<tr><td>202 Part 1 solutions</td></tr>
<tr><td>Energy Safe Victoria Act 2005</td><td>Electrical equipment</td><td>Same as Electricity Safety Act 1998</td></tr>
</table>

Regulation/ legislation		BIPV electrical requirements	Clause/ secondary referenced standards
	Electricity Safety (Equipment Safety Scheme) Regulations 2019	Electrical equipment certification, compliance and safety supporting part 4 Electrical equipment of the Electricity Safety Act 1998	All parts of the regulation
System-based requirements	AS/NZS 3000	Installation requirements	3.1 Selection and installation of wiring systems - General 4.1 Selection and installation of electrical equipment - General
		Overcurrent	1.5.9 Protection against overcurrent 2.5 Protection against overcurrent
		Spread of fire	1.5.12 Protection against the spread of fire 2.10.7 Fire-protection measures 3.9.9 Wiring systems selection and installation to minimise spread of fire 4.2.2.6 Prevention of spread of fire
		Overvoltage	2.7 Protection against overvoltage
		Arcing fault	2.9 Protection against fire hazard due to arcing fault
		Cabling	3.10 Enclosure of cables
		Selection and installation of PV systems	7.3.2 Selection and installation of electricity generation systems
			AS/NZS 5033
	AS/NZS 3013	Circuit integrity under fire conditions	Section 3 classification system

As shown in Table 6.1, AS/NZS 3000 states that the selection, installation, and control of electrical equipment intended to form a PV array system shall comply with AS/NZS 5033. As a recognised standard within the PV industry, AS/NZS 5033 sets out general installation and safety requirements for the electrical installation of PV arrays, including PV modules. Table 6.2 lists the electrical requirements relevant to BIPV fire safety in AS/NZS 5033.

Table 6.2 Electrical requirements relevant to BIPV fire safety in AS/NZS 5033

Regulation/ legislation	**BIPV electrical requirements**	**Clause/ referenced standard**	**Relevant tests**
AS/NZS 5033	Electrical safety requirements (such as electrical shock, overcurrent, arc fault, earth fault, lightning and overvoltage)	Section 3 Safety issues	NA
	Selection and installation of electrical equipment	AS/NZS 3000	NA
		Section 4 Selection and installation of electrical equipment	IEC 61730-2 IEC 61215-2
	Fire tests	Appendix I Fire tests, spread of flame and burning brand tests	AS 5033 (Appendix I)

As a specific type of PV, BIPV must comply with the requirements of PV modules. Table 6.3 shows the requirements and relevant tests of PV modules referred to in AS/NZS 5033. According to AS/NZS 5033, PV modules must comply with international standards IEC 61730-2 (Photovoltaic (PV) module safety qualification) and IEC 61215-2 (Terrestrial photovoltaic module - Design qualification and type approval). The tests in IEC 61730 are designed to assess the potential fire hazard due to the operation of a PV module or the failure of PV components. IEC 61730-2 refers to IEC 61215-2 and UL 1703 (Standard for Flat-Plate Photovoltaic Modules and Panels) for different requirements and tests (see Table 6.3). The ignition hazard is related to the requirements of insulation resistance, hot-spot endurance, diode junction temperature, and reverse current; electric shock hazard is related to wet leakage current. Four requirements and tests are related to ignition hazards in IEC 61215-2 which are referenced in IEC 61730-2: insulation resistance, hot-spot endurance, wet leakage current, and diode junction temperature, with the relevant tests. In addition, the requirements for and the relevant test related to electric shock hazard in UL 1703 are referenced in IEC 61730-2, such as reverse current. AS/NZS 5033 states that for building-mounted applications, the fire test requirement of IEC 61730-2 shall be Fire Class C or higher, based on the test procedure detailed in AS/NZS 5033 Appendix I. The fire resistance test is a basic test for PV. The proposed tests described in Appendix I in AS/NZS 5033 are derived from UL 790, which provides the test results of fire spread and ignition for PV panels. As required in AS/NZS 5033, additional requirements relating to fire resistance level may be applicable in accordance with the current NCC.

Table 6.3 Electrical requirements and relevant tests in AS/NZS 5033

Referenced standard	Electrical requirement	Relevant test	Referenced test
IEC 61730-2 **IEC 61215-2**	Insulation resistance	MST16 Electrical insulation test	IEC 61215-2 （MQT03）
	Hot-spot endurance	MST22 Hot-spot endurance test	IEC 61215-2 （MQT09）
	Wet leakage current	MST17 Wet-leakage current test	IEC 61215-2 （MQT15）
	Diode junction temperature	MST25 Bypass diode thermal test	IEC 61215-2 （MQT18）
IEC 61730-2	Reverse current	MST26 Reverse current overload test	UL 1703
Fire resistance and fire safety class		Appendix I Fire tests, spread of flame and burning brand tests	UL 790

6.2 Relevant tests

A failed electrical component is not necessarily the first component or material which ignites in the event of fire. The original electrical failure may occur in another device, inducing other electrical faults in nearby electrical devices, finally leading to fire. The ignition mechanisms may include several hazards, as indicated in Section 3.2. Ignition and fire may result from a chain of faults, causing difficulties in defining the root cause in many cases. For example, a loose connection may induce overheating in the electrical conductor, which may lead to combustible material igniting or destroying nearby insulation, leading to a short-circuit or arcing. Moreover, overcurrent in the cable may lead to either local overheating and ignition of combustible material or insulation failure and arcing or short circuit. One of the reasons for short circuits, earth faults and arcing is insulation failure due to several causes, including overheating due to electrical overloading, aged equipment or conductors, or loose connections. Although ignition can be caused for different reasons, all tests listed in Table 6.2 should be conducted on BIPV modules.

6.2.1 Fire Classification of PV modules

As indicated in AS/NZS 5033, for building-mounted applications, the fire test requirement of IEC 61730 must be Fire Class C or above, based on the test procedure provided in Appendix I of AS/NZS 5033. In IEC 61730, PV module fire performance requirements are detailed in ANSI/UL 1703, section 16, and test methods for PV fire performance classifications are specified in UL 790. However, the fire tests listed in Appendix I of AS 5033 are basic tests for PV panels.

Data required for AS/NZS5033 and related standards:

Secondary referenced standards:

IEC 61730-2 Photovoltaic (PV) module safety qualification

UL 1703 - Standard for Flat-Plate Photovoltaic Modules and Panels

Clause 31 fire tests of UL 1703 states that the distance of flame spread for different fire performance characterizations of modules must satisfy the following requirements:[6]

- Fire Class A: distance of flame spread less than 6 ft. in 10 minutes
- Fire Class B: distance of flame spread less than 8 ft. in 10 minutes
- Fire Class C: distance of flame spread less than 13ft. in 4 minutese

6.2.2 Insulation resistance

Hazard analysis: Generally, a short-circuit is the result of two conductors touching when they should not touch, resulting in very high currents, overheating, arcing, smoke, fire, and more short-circuiting. Overcurrent in a cable can cause local overheating and combustible material catching fire, as well as insulation failure and arcing or short-circuit. Insulation loss can produce short-circuits, earth faults, and arcing for a variety of reasons, including overheating due to electrical overloading or weak connections. Loose connections generate heat as current is run through them, resulting in insulation failure, arcing, etc (Troitzsch, 2016). The mechanisms of fire hazards are complex and interactive, and all of the hazards mentioned above are relevant to insulation.

Data required for AS/NZS 5033 and related standards:

Secondary referenced standards:

IEC 61215-2 Terrestrial photovoltaic module - Design qualification and type approval

IEC 61730-2 Photovoltaic (PV) module safety qualification

Clause 4.3 Insulation test (MQT 03) of IEC 61215-2 and MST 16 of IEC 61730-2 states that the insulation should satisfy the following requirements:

- No dielectric breakdown or surface tracking.
- Area $\leq 0.1\ m^2$, insulation resistance$\geq$ 400 MΩ; Area $> 0.1\ m^2$, $\text{insulation resistance} \times \text{ area} \geq\ 40M\Omega \cdot \mathrm{m}^2$

[6] For clarity, this refers to the system fire class rating for PV defined in UL1703, not the fire risk classes as defined in AS2444 (referenced by the NCC Volume 1 section E1.6).

6.2.3 Hot-spot endurance

Hazard analysis: Hot-spot is a phenomenon known to occur in PV cells under fault conditions such as partial shading, material imperfection, fabrication flaws or damage to the PV cell (Yang et al. 2015). This phenomenon is directly related to shadowing or shading. Generally, a hot-spot is caused by an excessive temperature rise on the surface of the front cover caused by a short circuit, which is likely caused by the reverse bias of PV cells due to partial shading (Pandian et al., 2016). Therefore, partially-shaded BIPV modules with hot-spots have the potential to ignite a flammable vapour cloud, causing a fire hazard. When the operating current of a faulty PV cell exceeds the reduced short-circuit current, it does not produce energy, but starts to consume power from the other PV cells connected in series, creating hot-spots on the surface. Generally, a hot-spot ignites a BIPV panel due to heating of the back sheet of the BIPV panel (Mazziotti et al., 2016). If the flammable vapour cloud is ignited, it can explode, producing a blast wave, which can cause major destruction over a large distance.

Data required for AS/ANZ. 5033 and related standards:

Secondary referenced standards:

IEC 61215-2 Terrestrial photovoltaic module - Design qualification and type approval

IEC 61730-2 Photovoltaic (PV) module safety qualification

According to Clause 4.9 Hot-spot endurance test MQT 09 in IEC 61215-2 and MST 22 of IEC 61730-2, no evidence of major visual defects is permitted for BIPV(PV) products, such as melted solder, openings in the enclosure, delamination and burn spots.

6.2.4 Wet leakage current

Hazard analysis: Wet leakage current may cause an electrical shock that may cause injury to firefighters or residents in a building when firefighters conduct rescue operations (Cancelliere, 2016).

Data required for AS/ANZ5033 and related standards:

Secondary referenced standards:

IEC 61215-2 Terrestrial photovoltaic module - Design qualification and type approval

IEC 61730-2 Photovoltaic (PV) module safety qualification

Clause 4.15 Wet leakage current test (MQT 15) of IEC 61215-2 and MST 17 of IEC 61730-2 state the passing criteria for this test as follows: Increase the voltage applied by the test equipment at a rate not exceeding 500 V/s to 500 V or the maximum system voltage for the module, whichever is greater. Maintain the voltage at this level for 2 min. Then determine the insulation resistance. This resistance should meet the requirements:

- For modules with an area of less than 0.1 m^2 the insulation resistance shall not be less than

400 MΩ.

- For modules with an area larger than 0.1 m^2 the measured insulation resistance times the area of the module shall not be less than 40 $M\Omega \cdot \mathrm{m}^2$.

6.2.5 Diode junction temperature

Hazard analysis: Exposure of_PV components to direct sunlight for a long time will likely result in overheating and may then cause electrical ignition when the temperature is high. Since the bypass diode is always inside the junction box, thermal effects after long-term exposure to the sun in normal service may also result in overheating (Resch-Fauster et al., 2017).

Data required for AS/ANZ5033 and related standard

Secondary referenced standards:

IEC 61215-2 Terrestrial photovoltaic module - Design qualification and type approval

IEC 61730-2 Photovoltaic (PV) module safety qualification

Clause 4.18 of IEC 61215-2 states that the diode junction temperature T_J shall not exceed the diode manufacturer's maximum junction temperature rating for continuous operation.

6.2.6 Reverse current

Hazard analysis: In an electric power system, overcurrent or excess current is a situation where a larger than intended electric current passes through a conductor, leading to excessive generation of heat, and the hazard of fire or damage to equipment. Protection shall be provided against injury or property damage, because overcurrent may cause excessive temperatures or electromechanical stresses (Yu et al., 2020).

Data required for AS/ANZ5033 and related standards:

Secondary referenced standards:

IEC 61730-2 Photovoltaic (PV) module safety qualification

UL 1703 - Standard for Flat-Plate Photovoltaic Modules and Panels

Reverse current is a current flowing in a reverse direction to the normal direction resulting from a normally illuminated PV module. According to Section 28 reverse current overload test of UL1703, the passing criteria are as follows: when a reverse current equal to 135 percent of the module or panel series overcurrent protective device rating current, the maximum external module surface temperature during the test as located by an infrared camera and measured by thermocouples shall not exceed 150° C and there shall be no flaming of the module or panel itself for 15 s or more, nor charring of the module or underlying support.

6.2.7 Leakage current

Hazard analysis: In most cases of PV fires the most likely cause is electrical arcing (Blazey

2017). Current leakage may cause arcing. Electrical arcing is the electrical breakdown of a gas that produces a prolonged electrical discharge leading to combustion. Effectively, a fire starts with a live wire sending electricity into the air. The temperature of an arc flash can reach several thousand degrees Celsius (Wang et al., 2014).

Data required for AS/ANZ5033 and related standards:
IEC 61730-2 Photovoltaic (PV) module safety qualification

UL 1703 - Standard for Flat-Plate Photovoltaic Modules and Panels

Section 21 Leakage current test in UL 1703 states that the leakage current of a module with a marked maximum system voltage of more than 30 V shall not be greater than the values specified as follows:

1. Maximum allowable leakage current for accessible conductive frame, pan or the like $\leq 10\ \mu A$
2. Maximum allowable leakage current for accessible circuit part $\leq$ 1mA
3. Maximum allowable leakage current for conductive foil over accessible insulation surfaces $\leq$ 1mA

6.3 Section summary

This section presents an overview of the relevant electrical requirements for BIPV materials in Victorian legislation. Section 6.1 presents the electrical requirements relevant to BIPV fire safety and Section 6.2 provides the relevant tests for the standards or regulations.

Section 7 Comparison with international regulations

This section compares the relevant fire safety regulations of Australia and other selected countries for electrical and building elements.

7.1 Specific standards for BIPV

Before 2020, the specific international and overseas standards for BIPV included ISO 18178, IEC 62980, EN 50583, and GB/T 51368. In 2020, IEC 63092 was published as the standard, based on the structure and content of EN 50583 and formally combining IEC 62980, with appropriate updates in accordance with EN 50583 and ISO/TS 18178. In addition, since 2019, GB/T 51368 has been adopted in China as the comprehensive guideline for BIPV modules. A brief introduction to these standards follows:

EN 50583-1 Photovoltaics in building- part 1: PV modules

EN 50583 focuses on the properties of PV modules which are relevant to the essential building and the applicable electro-technical requirements, as stated in the Low Voltage Directive (LVD) requirements. This standard is applicable to PV systems integrated into buildings, and solar panels used in construction. Modules with glass panes are further classified according to their mounting location in the building envelope. In addition to international PV standards such as IEC 61215 and IEC 61730, typical building standards such as BS EN:13501 series (Fire classification of construction products and building elements) are referred to in this standard.

ISO/TS 18178: Glass in building - Laminated solar photovoltaic glass for use in buildings

This standard focuses on PV glass applications and establishes safety requirements and test methods for laminated solar PV glass intended for use in buildings.

Laminated solar PV glass is laminated glass which incorporates PV energy generation functionality.

IEC 62980: Photovoltaic modules for building curtain wall applications

This standard defines the fundamental technical aspects of PV systems placed in buildings as curtain walls, as well as performance standards and test methods to ensure structural stability and electrical safety.

IEC 63092-1 Photovoltaics in buildings – Part 1: Requirements for building-integrated photovoltaic modules

This standard is based on EN 50583. Whenever feasible, words in the standard have been replaced with more broad language, and references to EN standards have been replaced by international standards.

IEC 63092-1 refers to the performance of PV based on the two series of standards, IEC

61215 and IEC 61730 discussed in Section 4. According to both IEC 63092 and IEC 61730, BIPV modules shall meet the fire safety requirements of the local national building code (or similar) for the building function they provide.

GB/T 51368 Technical standard for photovoltaic systems on buildings

This standard provides the requirements for BIPV modules in China. This standard is a comprehensive guideline for the application of BIPV, and includes the requirements for the materials, design, structure, electricity generation, and installation. This standard includes the requirements for each BIPV module component based on other Chinese standards, such as GB/T 20047.1, GB/T 9535, and others.

As a PV product, IEC 63092 refers to IEC 61215 and IEC 61730, which are standards for all PV systems. EN 50583, ISO 18178, and GB/T 51368 also refer to IEC 61215 and IEC 61730. Section 7.2 describes the relevant requirements of general PV modules in detail.

As BIPV is considered to be a building element, IEC 63092 states that the performance requirements must refer to local building codes, particularly in relation to fire safety. In particular, the fire requirements in EN 50583-1 are the same as those in EN 13501 part 1, part 2 and part 5, while GB/T 51368 requires that BIPV modules comply with the fire requirements in GB 50016. These standards are compared with the Australian national regulations in Section 7.3.

7.2 Requirements for PV modules

As electrical components, PV modules should meet the following requirements relevant to fire safety (Sahoo 2019):

- Insulation resistance and wet leakage current.
- Current and voltage characteristics
- Thermal performance (bypass diodes temperature, hot-spot endurance).

International standards IEC 61215 and IEC 61730 are the PV standards used in almost all regions globally, with the exception of the USA and Canada. If a PV module has been certified according to IEC 61215, this standard represents the quality of the module's application and compliance with electrical requirements. IEC 61215 is intended to apply to all terrestrial flat-plate module products such as crystalline silicon and thin-film modules. IEC 61730 is intended to ensure that PV modules provide electrical and mechanical operating safety during their entire expected service life. IEC 61730 specifies the fundamental construction requirements for PV modules in order to provide safe electrical and mechanical operation. UL 1703 Standard for Flat-Plate PV Modules and Panels is also an industry standard for baseline safety and performance. IEC 61730 refers to IEC 61215 and UL 1703 for different requirements (Figure 7.1).

Figure 7.1 shows the relevant standards for PV modules and performance requirements in different regions. EN 61215 and EN 61730 are widely used in Europe. In China, GB/T 20047.1 and GB/T 9535 also refer to IEC 61730 and IEC 61215. In Singapore, the CP5 in the Singapore national code and SS 601-1 both refer to IEC 61215.

As stated in Section 6, AS/NZS 5033 refers to IEC 61215 and IEC 61730, and the secondary referenced standard UL 1703. IEC 61730 refers to IEC 61215 and UL 1703 for different requirements and tests (see Figure 7.1). The tests in IEC 61730 are designed to assess the potential fire hazard due to the operation of a PV module or the failure of PV components. IEC 61730 refers to IEC 61215 and UL 1703 for different requirements and tests. There are four requirements and the related tests in IEC 61215-2 are referenced in IEC 61730-2, including: insulation resistance, hot-spot endurance, wet leakage current, and diode junction temperature. In addition, reverse current with relevant test in UL 1703 is referenced in IEC 61730-2.

UL 1703 is adopted in the USA and Canada. In addition to UL 1703, in the USA, the National Electrical Code (NEC) refers to NFPA 70 Article 690 as relevant requirements, including maximum voltage and direct current.

Furthermore, some national codes are used for different PV module components, including junction boxes, the associated cabling and the connectors at the end of the cabling. For example, in the USA and Canada, some standards need to be considered, such as UL 4703 (standard for PV wire), UL 6703 (Connectors for Use in Photovoltaic systems) and UL 3730 (Standard for PV Junction Boxes). Moreover, national electrical codes need to be considered when applying PV in or on buildings, such as SS 638 in Singapore and AS/NZS 3000 in Australia.

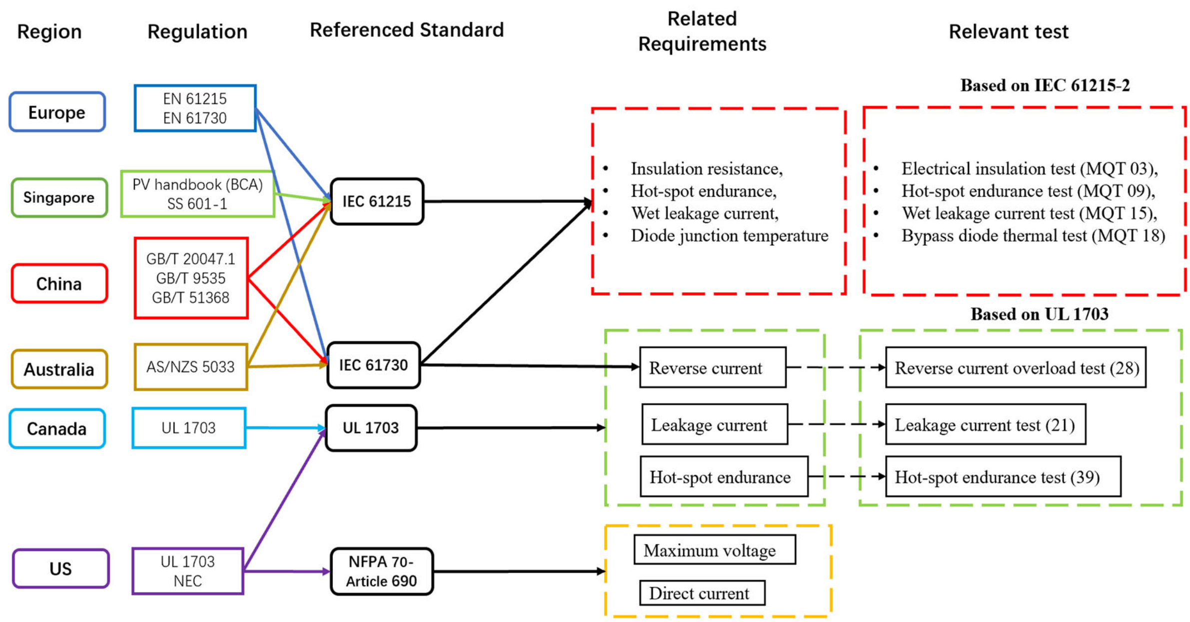

Figure 7.1 Standards and relevant electrical performance of PV modules in different regions

The detailed requirements are summarised in Table 7.1. Note that only the electrical requirements of PV/BIPV relevant to fire[7] are considered.

[7] As stated in Section 2, these electrical requirements of PV/BIPV related to fire are selected based on the causes

Table 7.1 Details of relevant requirements around the world

Electrical property	Related test	Requirements	Standard referred to
Maximum voltage		1. Maximum voltage of PV system DC circuit for residential buildings ≤ 600 V 2. Maximum voltage of PV system DC circuit for other building types ≤ 1000 V	NFPA 70 - Article 690
Direct current (DC)		Photovoltaic DC systems operating ≥ 80 W between any two conductors shall be protected by a PV arc-fault circuit interrupter or other equivalent protection.	NFPA 70 - Article 690
Leakage current	Leakage current test	1. Maximum allowable leakage current for accessible conductive frame and pan ≤ 10 μA 2. Maximum allowable leakage current for accessible circuit part ≤ 1mA 3. Maximum allowable leakage current for conductive foil over accessible insulation surfaces ≤ 1mA	UL 1703
Reverse current	Reverse current overload test	When a reverse current equal to 135 percent of the module or panel series overcurrent protective device rating current, the maximum external module surface temperature during the test as located by infrared camera and measured by thermocouples shall not exceed 150° C and there shall be no flaming of the module or panel itself for 15s or more, nor charring of the module or underlying support.	UL 1703
Insulation resistance	Electrical insulation test	1. No dielectric breakdown or surface tracking. 2. Area ≤ 0.1 m^2, insulation resistance ≥ 400 MΩ 3. Area > 0.1 m^2, insulation resistance × area ≥ 40$M\Omega \cdot \mathrm{m}^2$	IEC 61215-2, 4.3

of BIPV fire hazards. Installation errors and arcing faults require insulation resistance, wet leakage current, maximum voltage, direct current, reverse current and leakage current; hot-spots require diode hot-spot endurance; junction box errors require diode junction temperature; electric shock requires wet leakage current.

Electrical property	Related test	Requirements	Standard referred to
Hot-spot endurance	Hot-spot endurance test	No evidence of major visual defects permitted, such as melted solder, openings in the enclosure, delamination and burn spots.	IEC61215-2, 4.9
Wet leakage current	Wet-leakage current test	Increase the voltage applied by the test equipment at a rate not exceeding 500 V/s to 500 V or the maximum system voltage for the module, whichever is greater. Maintain the voltage at this level for 2 min. Then determine the insulation resistance. This resistance should meet the requirements: - Module area ≤ 0.1 m^2, insulation resistance≥ 400 MΩ - Module area > 0.1 m^2, insulation resistance × area ≥ $40M\Omega \cdot \mathrm{m}^2$	IEC61215-2, 4.15
Diode junction temperature	Bypass diode thermal test	The diode junction temperature T_J shall not exceed the diode manufacturer's maximum junction temperature rating for continuous operation	IEC61215-2, 4.18

In addition to the requirements shown in Table 7.1, there are two main differences between UL 1703 and IEC 61215:

1) the system voltage when testing for UL 1703 is generally 600 Volts, whereas for IEC 61215 the voltage is generally 1000 Volts.

2) the test methods specified in UL 1703 and IEC 61215 differ greatly. The most typical test is the hot spot endurance test, and the two standards are very different in the way they examine the safety of modules under abnormal conditions.

Generally, IEC 61215 and UL 1703 are two standards which evaluate PV/BIPV modules using their own sets of tests. Although there are many differences between these two standards, the purpose of these standards is the same as the examination of the safety and performance of BIPV modules. Australia does not have major differences with the fire safety requirements for PV modules of other regions, especially Europe and China.

7.3 Relevant requirements for applicable building elements

As stated in Section 7.1, the fire requirements for a building element with a BIPV module must comply with local codes. Therefore, this section compares the fire safety requirements of building elements in different regions. The relevant performance and test standards in the investigated countries are shown in Table 7.2.

Table 7.2 Performance regulations and test standards in investigated countries

Country	National regulation	Relevant test standard		
Australia	National Construction Code (NCC)	AS 1530.1		Methods for fire tests of building materials, components and structures Part 1: Combustibility test for materials
		AS 1530.3		Methods for fire tests of building materials, components and structures Part 3: Simultaneous determination of ignitability, flame propagation, heat release and smoke release
		AS 1530.4		Methods for fire tests of building materials, components and structures Part 4: Fire-resistance tests for elements of construction
		AS 5113		Classification of external walls of buildings based on reaction-to-fire performance
The UK	Approved document B	EN 13501-1 EN 13501-2 EN 13501-5	EN 1182	Reaction to fire tests for products — non-combustibility test
			EN 1716	Reaction to fire tests for products - Determination of the gross heat of combustion (calorific value)
			EN 13823	Reaction to fire tests for building products — Building products excluding floorings exposed to thermal attack by a single burning item
			EN 11925-2	Reaction to fire tests - Ignitability of products subjected to direct impingement of flame - part 2 Single-flame source tests
The USA	NFPA 5000	ASTM 136		Standard Test Method for Assessing Combustibility of Materials Using a Vertical Tube Furnace at 750°C
		NFPA 285		Standard Fire Test Method for Evaluation of Fire Propagation Characteristics of Exterior Wall

<table>
<tr><th>Country</th><th>National regulation</th><th colspan="3">Relevant test standard</th></tr>
<tr><td rowspan="3"></td><td rowspan="3"></td><td></td><td colspan="2">Assemblies Containing Combustible Components</td></tr>
<tr><td>UL 790</td><td colspan="2">Standard Test Methods for Fire Tests of Roof Coverings</td></tr>
<tr><td>UL 263</td><td colspan="2">Fire Tests of Building Construction and Materials</td></tr>
<tr><td rowspan="3">Canada</td><td rowspan="3">Nation Building Code of Canada (NBCC)</td><td>ULC-S135</td><td colspan="2">Standard test method for the determination of combustibility parameters of building materials using an oxygen consumption calorimeter (cone calorimeter)</td></tr>
<tr><td>CAN/ULC-S134</td><td colspan="2">Standard Method of Fire Test of Exterior Wall Assemblies</td></tr>
<tr><td>UL 790</td><td colspan="2">Standard Test Methods for Fire Tests of Roof Coverings</td></tr>
<tr><td rowspan="4">China</td><td rowspan="4">GB 50016</td><td>GB/T 9978-1</td><td colspan="2">Fire-resistance tests-Elements of building construction-part1: General requirements</td></tr>
<tr><td>GB/T 8626</td><td colspan="2">Test method of flammability -Building materials</td></tr>
<tr><td>GB/T 14402</td><td colspan="2">Reaction to fire test for building materials and products-Determination of the heat of combustion</td></tr>
<tr><td>GB/T 20284</td><td colspan="2">Single burning item test for building materials and products</td></tr>
<tr><td rowspan="4">Singapore</td><td rowspan="4">Code of Practice for Fire Precautions in Buildings 2018 (Fire code 2018)</td><td rowspan="4">EN 13501-1</td><td>BS 476:20-23</td><td>Fire Resistance Test to Building Material</td></tr>
<tr><td>BS 476-11</td><td>Fire tests for assessing the heat emission from building materials</td></tr>
<tr><td>BS 476-6</td><td>Fire tests on building materials and structures — Part 6: Method of test for fire propagation for products</td></tr>
<tr><td>BS 476-7</td><td>Fire tests on building materials and structures Part 7. Method of test to determine the classification of the</td></tr>
</table>

Country	National regulation	Relevant test standard		
				surface spread of flame of products
			ASTM E108	Standard Test Methods for Fire Tests of Roof Coverings

First, the performance requirements are determined by the building classification, which means the assessment of fire safety may have different results due to differences in building classifications, even for the same building material. Moreover, the definition of combustibility significantly affects the use of building materials. For most national regulations, a material's non-combustibility of materials is used to judge the feasibility of the material being applied in building construction. If the building material is non-combustible, it can be used on buildings in the studied regions. Otherwise, combustible material is only allowed in specific circumstances. Moreover, the fire safety requirements differ for each building element, including external walls, roofs/skylights, windows and other openings, and ancillary elements.

Therefore, the comparisons in this section include building classifications in each region, the definition of non-combustible material, and the performance criteria for different building elements in Australia, the UK, the USA, Canada, China and Singapore. The fire performance requirements are presented according to the building element (external wall, roof/skylight, window and other opening, and ancillary element/attachment). Detailed comparison tables are presented in Appendix B.

7.3.1 Building Classification

As shown in Appendix B, Table B.1, building classifications in most regions are determined by the use of a building. Compared with Australia, the UK, Canada, and Singapore have similar building classifications, and buildings are classified as residential or non-residential in these countries. The definition of residential buildings is based on general residential buildings and buildings providing care, rental accommodation, treatment, and other more short-term purposes. Non-residential buildings generally include office buildings, shops, and commercial, industrial, and storage buildings. Assembly buildings or places of public resort are considered a specific building type in the UK, Canada and Singapore. While the NCC defines three building construction types and defines the level of fire resistance based on the number of floors of building and the building classification, Canada and Singapore do not identify the construction types in terms of the levels of building, and the requirements of fire performance in the UK are different when the building height is more than 18 m or less than 18 m. In China, although buildings are classified as either residential or non-residential (public buildings), residential buildings are classified in terms of their height, and the classification of public buildings depends on their use and capacity. In contrast, the definition of building type for the assessment of fire hazard in the US is based on the building material, which is significantly different from building classification in Australia.

7.3.2 Non-combustible material

While the definition of non-combustible material is directly related to whether the specific material can be used in building elements, the performance requirements of non-combustible material shown in Table B.2 are determined based on various factors, such as temperature rise, flaming, debris, and smoke. Like the Australian requirements, the US and Canadian requirements also refer to temperature rise. The UK standard (EN 13501-1) and the requirements in Canada (ULC-S135) and Singapore (BS 476 Part 4) similarly require sustained flaming.

Both Australia and the UK require the temperature rise to be no more than 50 °C, and Singapore requires that the temperature rise in a furnace shall be not more than 20°C and 25°C, depending on the density of the material. In comparison, the US requirements require the temperature rise to be less than 30 °C if the weight loss is 50 % or less and not above the stabilised furnace temperature if the weight loss exceeds 50 %. The Canadian requirement is that the average heat release should be no more than 3 MJ/m^2 instead of the temperature rise.

In relation to sustained flaming[8], the national regulation in Australia requires the mean duration of sustained flaming to be zero, while the duration of sustained flaming in the UK must be less than 20s according to EN 13501-1. The Singaporean regulation states there shall be no flame if the material density is more than 300 kg/m^3 or not more than 10 s for density less than 300 kg/m^3. In the USA, ASTM 136 requires no flaming during the test or for a certain duration in terms of the weight loss of the specimen.

In the UK, EN 13501-1, and in Canada, ULC-S135 also include the requirement of smoke developed, which is not included in AS 1530.1, while EN 13501-1 requires that the smoke growth rate (SMOGRA) and total smoke production within 600s (TPS600s) shall be less than 30 m^2/s^2 and 50 m^2, respectively. Regarding ULC-S135, the average smoke extinction area is required to be less than 1.0 m^2 in Canada.

7.3.3 External walls

7.3.3.1 Reaction to fire

When national requirements permit limited combustible material to be used on external walls (such as in the UK, the US, and Canada), or the performance criteria of fire spread are one of the pathways to assess the fire resistance of external walls (such as in Australia), the performance requirements of fire reaction mainly include temperature rise, flame spread, and heat release (refer to Table B.3).

The regulations in Australia and the USA state the requirement of temperature rise. According to AS 5113, for an external wall system with BIPV components, the temperature rise shall not exceed 600 °C and 250 °C for the exposed specimen face, which is 4 m (according to ISO 13785) or 5 m (refer to BS 8414) above the opening and the mid-depth of the BIPV layer or

[8] sustained flaming means the outcome of a successful fire ignition and encompasses three factors \
: ignitability, sustainability and combustibility (Beverly and Wotton, 2007).

the cavity (according to ISO 13875) or 5 m (refer to BS 8414) above the opening, respectively. Compared with Australian regulations, in the USA, NFPA 5000 demands that the temperature in BIPV components shall not exceed 417 °C above their temperature measured immediately after the start of the fire test, and the temperatures in the air cavity shall not exceed 538 °C. In addition, AS 5113 requires that the temperature rise on the unexposed face of an external wall system 900 mm above the opening shall not exceed 180 K if the external wall is not required to have a fire-resistance level of -/30/30 or 30/30/30 or more.

No flaming in an area of external wall or limited distance of flame spread is another crucial requirement of the national regulations in the regions studied. In Australia, AS 5113 states that flame spread should not occur at openings in the exposed face of external walls or beyond the confines of the specimen. In the USA, flame propagation on the exterior face of the test specimen shall not occur either vertically or horizontally beyond a certain area. Flames shall not occur in a second-storey test room or beyond the test specimen's intersection and the test apparatus's side walls. In the UK, EN 13501-1 requires that there shall be no flame spread in excess of 150 mm vertically from the point of application of the test flame within 60 s from the time of application, and no lateral flame spread to the edge of the specimen. The Canadian regulation also specifies the distance of flame spread, which shall be no more than 2 m above the opening. In addition, heat flux during flame exposure on a wall must not be more than 25 kW/m^2 at 3.5 m above the opening.

In addition, compared with the Australian standards, the UK and the USA set additional requirements in relation to heat release to determine the class of limited combustible material. While the requirement of total heat release in EN 13501-1 is 7.5 MJ in 600 s, total heat released shall not exceed 8 MJ/m^2 when the test complies with ASTM E2965 in the USA, and the peak heat release shall not exceed 150 kW/m^2 for longer than 10 s when the sample is tested in accordance with NFPA 259.

7.3.3.2 Fire resistence

In all investigated regions, the performance requirements of fire resistence include the parameters of structure stability, integrity, and insulation. The fire resistance requirements for building elements are governed by the building height and/or the distance from a fire source. In Australia, the regulations take into account the building class, rise in storeys, indicated by construction type (A,B or C) and distances from a fire source (less than 1.5 m, or 1.5 m to less than 3 m), while the requirements in the UK are based on building height (up to 5 m to up to 30 m), and fire-resistance ratings in the US depend on horizontal separation. In addition, the regulations in Singapore specify fire resistance in terms of different building dimensions of the building purpose group.

In relation to the detailed values shown in Appendix B Table B.4 – D.9, the requirements in Australia and UK specify only the duration of integrity and insulation for non-loadbearing external walls. In contrast, the fire resistance value of BIPV external walls should satisfy all three parameters in the USA, China and Singapore. Compared with other regions, the Australian requirement of duration is longer in most scenarios.

7.3.4 Roof or skylight

7.3.4.1 Reaction to fire – flame spread

According to the summary of national requirements (see Table B.10), the requirement of fire reaction for BIPV roofs or skylights is mainly determined according to flame spread.

For roofs or roof coverings, there are no requirements regarding flame spread in Australia (though there are various other fire related requirements for roofs and roof coverings within NCC 2019) and the UK. Requirements in the USA and Canada are based on UL 1703, and the requirements in Singapore are in accordance with ASTM E108. According to Table B.10 and B 11, NFPA 5000 requires that BIPV roof covering satisfies Class B[9] at least for most construction types, with the exception of specific construction types, including 'Unprotected Combustible[10]' and 'Unprotected Ordinary' constructions which only need to satisfy Class C[11] in terms of the requirements of UL 1703. Class B in UL 1703 means that flame spread is less than 8 ft (2.44 m) in 10 minutes, while Class C means flame spread is less than 13 ft (3.96 m) in 4 minutes. In Singapore, the material of roof coverings shall be class A[12] in accordance with ASTM E108, with the exception of PG I and PG II or buildings with automatic sprinkler systems. Flaming shall not spread beyond 6 ft (1.8 m) for Class A in accordance with ASTM E108. In addition, if the building is less than four storeys, or the roof space is divided by cavity barriers and openings in the cavity barriers have fire-stop measures, or the underside of the roof as a ceiling to a room or space comply with the relevant provisions, types PG III, IV, V, and VII buildings are permitted to use combustible material on the roofs.

Regarding skylights, there are no specific requirements regarding flame spread for skylights in China and Singapore. The regulations in Australia, the UK, and Canada do refer to flame spread, but the detailed requirements differ (and again, there are various other fire related requirements for skylights within NCC 2019). In Australia, according to AS 1530.3, an index of 9 for spread of flame means the range of '1.33 * Mean Propagation Time' is from 10 s to 30 s, and the index of 8 for smoke developed means the mean optical density[13] is from 1.05 to 2.10. Compared with Australia, the duration described in the UK standard (EN 13501-1) is the duration of specimen burning after the withdrawal of the test flame, and the flame spread distance shall be less than 0.38 m across the region of burning. In Canada, skylights can be used on buildings if they meet the flame-spread rating of 150 (or 75) if the skylights have an individual area of not more than 9 m^2 (or 27 m^2), and have an aggregate horizontal projected area of openings through the ceiling not more than 25% (or 33%) of the area of the ceiling of the room or space in which they are located, and are spaced not less than 2.5 m (1.2 m) from adjacent assemblies and from required fire separations. The values are defined by a calibration material, red oak, in 10 minutes, which means that this is the distance from the ignition position to the burning position in 10 minutes. The basic distance of 100 m is defined using red oak. Therefore, 75 and 150 are

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[9] Class B in this section is the classification in UL 1703

[10] Also known as "ordinary" construction, this type has brick or block walls with a wooden roof or floor assembly which is not protected against fire (Construction Types -Definitions, 2022).

[11] Class C in this section is the classification in UL 1703

[12] Class A in this section is the classification in ASTM E 108

[13] Optical density means the logarithmic intensity ratio of the light falling upon the material (Zhang and Hoshino, 2013)

the distance between the ignition position to the final burning position based on the calibration material red oak.

7.3.4.2 Fire resistance

In Australia and the USA, regulations specify the values of fire resisting for BIPV roofs shown in Table B.10 to B 13. According to the NCC, only Type A constructions have a requirement of fire resistance for roofs. A comparison of the fire resistance requirements in these two countries indicates that NCC in Australia has higher requirements for structural stability and integrity parameters, and Type I in NFPA 5000 also requires a high value of fire resistance. Otherwise, the requirement of insulation in most scenarios in Australia is only 30 mins, with the exception of Class 7b and Class 8. Similarly, the requirement of the other four types of buildings in the USA are not more than 1 hour when the construction type is non-combustible, protected non-combustible, protected ordinary, or protected combustible.

7.3.5 Windows and other openings

According to the detailed requirements stated in Appendix B Table B.14, similar to Australia, the regulations in most countries require vertical separation to mitigate the fire hazard of BIPV windows and other openings. In Australia, when the offset between two vertical opening is less than 450 mm, the two openings shall be separated by a vertical spandrel or a horizontal projection.[14] The similar requirement of distance in the US is a radius of 1525 mm. In addition, the Chinese code states that vertical separation should be set if the vertical distance between openings is less than 1.2 m. If there is a sprinkler system, the requirement of vertical distance is 0.8 m. According to the Approved Document B in the UK, window frames and glass (including laminated glass) are exempt from the requirement of resisting fire spread. Other countries do not specify the distance between BIPV windows and other openings and the boundary, which is a requirement of the NCC.

7.3.6 Ancillary elements

As the comparison shown in Appendix B Table B.15 indicates, in the studied regions, similar to Australia, the USA and Singapore have requirements concerning fire resistance, index of flame spread, and smoke developed. In Australia, the requirements for ancillary elements include flame spread and smoke developed, and the values of these two parameters for ancillary elements are the same as those for skylights (see Table B.10). Combustible coverings in the USA must satisfy a flame spread index of 0-25, and a smoke developed index of 0-450 in accordance with ASTM E84. The flame spread index is determined in terms of the total area from the time-temperature curve, and the area under the curve of time-absorption shall be divided by the area under the curve for heptane, multiplied by 100, and rounded to the nearest multiple of five to establish a numerical smoke-developed index. In Singapore, the requirements include one-hour fire resisting and classification of flame-spread rating. Construction of attachments, such as awnings or canopies, is permitted in some specific

[14] NCC Volume 1 C2.16 is applicable only for buildings required to be of Type A construction that are not protected by a sprinkler system. For the protection of windows and other openings, requirements are outlined in NCC Volume 1 Part C3.

scenarios in the other three countries. In other words, ancillary elements/attachments can be used in some specific scenarios in the UK, Canada, and China without the requirement of non-combustibility.

7.4 Section summary

The main results of the comparison are as follows:

- The electrical fire safety requirements of PV modules in Australia and other countries, except for the US and Canada, are based on the same international standards, such as IEC 61730 and IEC 61215.
- The studied countries have different fire safety requirements on building elements mainly including the following aspects:
    i. The classification of buildings has two methods: the use of buildings, and building height. The minimum technical requirements (i.e. 'performance requirements' in the Australian NCC) for a new building or new building work in an existing building are determined by its classifications.
    ii. Differences in the definition of non-combustibility include temperature rise, sustained flaming and smoke development.
    iii. In relation to an external wall's reaction to fire, the studied countries have different requirements for temperature rise and flaming for external walls and the fire resisting levels have different requirements for duration.
    iv. Flame spread is the main difference in reaction to fire in roofs, and the requirement of duration is the difference of fire resisting level in roofs.
    v. The studied countries have different distance requirements for vertical separation of windows.
    vi. Flame spread, smoke development and fire resisting level have different requirements for ancillary elements in the countries.
- Some of the performance criteria of non-combustible materials, reaction to fire of external walls, and roof coverings in other standards are not considered in the Australian regulations. For example, AS 5113 does not include the heat release value to evaluate fire spread on external walls. However, this parameter is considered in the UK (EN13501) and the USA standards (NFPA 285). For instance, EN 13501 specifies the total heat release in 600 s shall be less than 7.5 MJ.

Section 8 Future research directions

Based on the literature review and interviews, this section recommends future research directions related to BIPV fire safety. Section 8.1 lists potential measures to mitigate the fire hazards identified in Section 3, Section 8.2 suggests future research directions for BIPV module tests, Section 8.3 is related to future product innovation, and Section 8.4 discusses recommendations for standards or regulations.

8.1 Measures to mitigate hazards

8.1.1 Measures to mitigate the likelihood of fire spread

As the introduction in Section 3, fire propagation is one of the main fire hazards generated by BIPV modules. However, there are gaps in suitable fire prevention and protection measures. Further discussions should be conducted to resolve this issue, focusing on, but not limited to, the following aspects:

- Although wall wetting sprinkler systems are a common measure to mitigate fire spread, they cannot stop energy generation by BIPV modules in fire conditions under sun exposure.

- A building's sprinkler system is generally designed for a limited number of sprinkler heads to operate simultaneously, and its unknown limitation in stopping a large caused by the vertical fire spread via BIPV modules.

- The fire spread to multiple floors simultaneously may also affect the number of hydrants required to be operated by an attending brigade during a fire. An appropriate strategy should be designed for water supplies and system infrastructure for hydrants and sprinkler systems.

- When BIPV modules are applied to façades of high-rise buildings, vertical fire spread may prevent fire brigades from attacking fires from the outside. Therefore, it is necessary to consider research on fire and rescue operations.

- The feasibility of adding a layer at the rear of the BIPV back sheet, such as a fireproof membrane, should be considered. Such a layer would act as a barrier to stop flame spread from the BIPV backsheet or to shield the radiative heat.

- Relevant design and engineering measures need to be considered to mitigate fire spread from one fire compartment to another fire compartment on the same floor.

8.1.2 Investigation of the impact of different evacuation strategies

When BIPV modules are integrated with building façades, potential hazards are flame and smoke development, which can affect the evacuation of occupants. As the introduction in Section 3, building design strategies impact evacuation in fire conditions. Therefore, a future research direction is to analyse the flame spread and smoke development of BIPV modules in various building design scenarios using a quantitative approach. Discussions can be conducted to explore potential measures to mitigate hazards during the evacuation process.

8.1.3 Measures to interfere with falling debris

Falling debris as one of potential hazards for evacuees has been presented in Section 3. Therefore, measures need to be conducted in future research to avoid the installation of BIPV modules above exits which can be one way of mitigating the hazard of falling panels onto the evacuees.

8.1.4 Measures and innovations to mitigate the hazard of partial shading of BIPV modules

As a consequence of partial shading, hot-spots may result in unusually high cell temperatures of BIPV modules, creating fire hazards. Hot-spots are caused by shading patterns, shading areas and shading location of BIPV modules (Yoo 2011). Active bypass circuits based on bipolar transistors have been developed, which significantly boost the output of BIPV modules compared with conventional bypass diodes (Ziar, Farhangi & Asaei 2014). Another practical mitigating measure is the use of module-level power optimisers (PV optimisers), which sit on the back of each solar panel. These PV optimisers are controlled by one central unit, enabling the shutting down of power to each module individually. The way to trigger the PV optimiser to turn off the module is by disconnecting the AC power to the inverter; then, when an earth fault or arc fault occurs anywhere in the BIPV system, it will turn off the BIPV modules with hazards. However, cutting off the current on the vertical wall is still an issue because BIPV modules are not only connected to the electricity distribution system but are also integrated into the wall system of the building. BIPV partial shading is more critical than that for roof-mounted PV due to the impact of the neighbourhood on the façade. Microinverters and PV optimisers may be a potential hazard mitigation measure for hot spots due to partial shading. A micro-inverter is sized to suit individual BIPV panels rather than a string of BIPV modules. By having a microinverter on each BIPV panel, the outputs are completely independent of each other, so that a hot-spot only affects a specific BIPV panel but not the whole system (Çelik, Teke & Tan 2018). Further research should be conducted to mitigate and understand the impacts of partial shading on BIPV.

8.1.5 Measures to mitigate fire hazards of BIPV module connectors

In addition to fire hazards which may occurs at the individual BIPV module, the major reason for large fires is the connections to other BIPV modules and back into the installation wiring. Due to human error, the connectors may be mismatched from different connector brands. BIPV module connectors may be one of the sources of ignition within the system. Traditional PVs are installed on non-combustible roofs, and if the connectors fail, the burning BIPV modules may be contained outside the building for a while. In contrast, if BIPV modules are used as the façade of a building, if the back sheets of the BIPV modules catch fire, the ignition source is actually on the internal wall, which depends on the installation of the modules and the connectors from modules to installation wiring. Mitigation measures could include, but not limited to, professional training and regular maintenance and inspection. Future research should further explore feasible measures.

8.1.6 Measures to mitigate the hazard of lightning when BIPV is used as part of a façade system

AS 1768:2021 'Lightning protection' stipulates the requirements that must be met for the design, installation, maintenance, and testing of lightning protection on common structures, as well as for the electrical and electronic systems in those structures. These requirements are intended to protect people and property from the hazards posed by lightning. AS1768 has been recently updated to include protection of PV systems installed on roofs. However, it does not specify the requirements for PV integrated to building vertical surfaces. It is recommended to amend AS 1768 with further requirements for buildings with BIPV façades, and these requirements may be the result of further research.

8.1.7 Measures or system innovations to mitigate electric shock hazard for fire rescue personnel

Since burning BIPV modules may still generate electricity, electric shock is a potential hazard to firefighters and building occupants. Electric shock may have severe consequences such as electrocution. Safe firefighting efforts require the building's electrical power to be removed before the water is applied. It is difficult to switch off a BIPV system during a fire to ensure all components are de-energised (Tommasini et al. 2014). Future research could consider the measures or product innovations to create a protective coating for insulating the module from light (e.g. sunshine) should a fire occurs. Options such as PV optimisers or the Internet of Things to cut off the current or switch the system off could also be considered in future research. Protective clothing and fire rescue equipment could also be identified in future studies. Furthermore, the location of any mitigation measures such as electrical isolation switches needs to be considered relative to the location of potential BIPV fire-affected areas, as attending fire service personnel need to safely access these locations.

8.1.8 Investigation of the impact of other electrical components on BIPV modules and buildings

Although batteries are not a compulsory system component for BIPV projects, they are still a critical concern as a fire hazard (Kim, A.A et al, 2019). Future research may focus on mitigating battery-related fire hazards and paying more attention to equipment designed for use in fires involving batteries and battery systems. Inverters and isolators may also be critical hazards for PV systems. Usually, batteries, isolators and inverters are not installed as building elements. However, if these electrical components are located in areas forming part of building façades, such as microinverters, it would also be helpful to understand their impact on vertical fire spread. Future research should be conducted regarding regulations on the fire safety requirements of batteries, isolators and inverters. How these electrical components contribute to the overall fire hazard as part of BIPV systems and how they affect BIPV modules require study. For instance, if inverters were reported as the leading cause of BIPV-related fires, it would be crucial to understand their proximity to the BIPV system components and possible fire spread, and separating inverters from other BIPV components may be an essential requirement for safe design.

8.2 Recommendations on test configurations

8.2.1 Specimens of BIPV modules

As stated in the introduction to the previous section, PV components generally include PV cells, encapsulants, front covers, back covers, laminates, junction boxes, and cabling. Therefore, evaluating BIPV modules should consider as a system. Regarding the back cover, the damage zone and the reaction to fire classification are determined in terms of the material of the back sheet (Cancelliere and Liciotti, 2016). An electrical element in BIPV modules, junction boxes also affect the combustibility of BIPV modules. If the junction box is exposed to a fire source, there is a high fire hazard for the BIPV module (Huang *et al.*, 2018).

Therefore, to assess the fire behaviour of BIPV modules, all components need to be tested. It is necessary to consider how the electrical parts of BIPV modules affect the test results. For instance, the presence and the number of junction boxes and cables may show different behaviours during testing. Therefore, future research should be conducted to confirm the selection of test samples.

8.2.2 Methods to keep BIPV modules active during fire tests

As previous introduction, a potential fire hazard of BIPV modules is the possibility that the system remains operational when a fire occurs. In other words, the assessment of the fire resisting of BIPV modules should not only consider the fire resistance level of the material and the reaction to fire of modules, but also estimate the hazard of a system which is operating. However, limited cases conducted in current stage take this effect into account. For example, according to the review of current research, such as the testing of the fire behaviour of PV module back sheets (Cancelliere and Liciotti, 2016), the testing of different installation positions of junction boxes (Huang *et al.*, 2018), and the testing of the burning behaviours of PV panels with different coverings (Ju *et al.*, 2017), BIPV modules do not remain active in all tests of BIPV modules. Therefore, further research should be conducted on how to keep BIPV modules active during relevant tests.

8.2.3 Evacuation of electric shock hazard in tests while BIPV modules are active

If the fire brigade employs water-based extinguishing agents while BIPV modules are active, firefighters could receive electric shocks (Tommasini et al., 2014). In order to protect firefighters from being electrocuted by the conductivity of water, it is usually necessary to turn off the building's power supply before undertaking firefighting operations. However, BIPV systems may continue to generate electricity when exposed to light, even if there is a fire. Therefore, the safe distance between firefighting equipment and active BIPV components should be determined. There needs to be further research on how to evaluate the safe distance when BIPV modules are tested in active mode.

8.2.4 Test configurations and development of tests on toxic smoke

The previous section has mentioned that toxic smoke is one of the potential hazards for building occupants. However, there is no existing requirement for monitoring toxic smoke emitted from BIPV modules in Australia. Therefore, further research should be conducted on the impact of toxic smoke from BIPV modules based on tests or building design strategies.

8.2.5 Suggestions for common structure/design configurations for fire safety tests

Large-scale tests can contribute many more details of fire performance, especially regarding the connection between fire compartments. However, since BIPV can be used as different building elements with a variety of structures and design configurations, it is not cost-effective for BIPV manufacturers to test all design scenarios. In addition, there is no test for BIPV modules which is recognised in Australia. Therefore, future research should be conducted to provide suggestions on the recommended structures and design configurations to be used in tests to provide detailed knowledge to fire safety engineers of the performance of BIPV modules.

8.3 Product innovation

8.3.1 Measures and innovations to avoid the ignition of BIPV modules

(1) Ignition of cabling and junction boxes

Cabling and junction boxes are important electrical components of BIPV modules which is introduced in Section 3. Compared with other components, such as isolators or batteries, cabling and junction boxes are more closely connected to the BIPV panel outside the building, which means the potential fire hazard caused by cabling and junction boxes significantly impacts the fire resistance of building elements with BIPV modules.

To resolve this issue, possible approaches include reducing the possibility of ignition of cabling and junction boxes and limiting flame spread from cabling or junction boxes to other components. For example, compared with direct exposure, a junction box in a BIPV module shows better resistance to fire (Huang *et al.*, 2018). However, the positioning of the junction box is only a measure to decrease the possibility of ignition rather than to avoid ignition, which is still a gap in current research. Therefore, future research should be conducted on material innovations to reduce the ignition hazard of cabling and junction boxes.

(2) Less ignitable and flammable materials/coatings for BIPV

According to the descriptions of fire hazards of BIPV modules in the previous section, it is recognised that one of the main reasons for fire is the use of combustible material in BIPV modules, which can result in the flame spread and debris dropping. Therefore, future research should consider the product innovation of less ignitable and flammable materials/coatings for BIPV.

8.3.2 Product innovation to improve the fire-resisting level of external walls or roofs with BIPV modules

For any building element, the capacity of fire resisting is one of the major safety requirements, and presents the last line of protection from fire if other measures fail (Hurley, et al, 2015).

Sufficient fire resistance level of a building element means how long the building element can maintain its performance or delay the spread of fire (Chow and Chan, 1996). Structural adequacy, integrity, and insulation are three parameters that determine the fire resistance level of a building element. Structural adequacy means the capacity to avoid structural collapse, while integrity and insulation mean the prevention of flame breakthrough and heat transfer, respectively. Future research can be conducted on innovations to produce highly fire resistant BIPV building elements.

8.4 Suggestions for standards or regulations

8.4.1 Proposals for including BIPV requirements in AS/NZS 5033

AS/ NZS 5033 sets out general installation and safety requirements for electrical installations of PV arrays, including wiring systems, electrical protection devices, and switching and earthing provisions. However, there are insufficient requirements for BIPV modules in AS/NZS 5033. For example, traditional PV systems installed on roofs may remain contained outside a building when a fire occurs. In contrast, when PV modules are integrated with building façades, such as curtain walls or double-skin façades, modules can be a fire hazard because cabling systems installed on the back of panels are exposed to the indoor area. The ignition of the cabling system could suddenly result in fire propagation to the internal parts of the building. Vertical fire propagation by cabling systems may also cause a fire hazard to higher levels. Severe burning of the cabling system may break through the BIPV panels, and flame spread to surrounding buildings. To avoid the ignition of cabling in BIPV modules, the cabling of BIPV modules needs better fire performance. Cabling management of BIPV modules is also a concern. Animals (such as pests, rats and possums) coming behind the panels may cause damage to the insulation of the cabling, causing the short-circuiting of BIPV modules, leading to a potential fire. BIPV systems may require higher levels of cabling management than traditional PV systems. In summary, future research should consider what requirements need to be included in AS/NZS 5033 to mitigate the fire hazard of BIPV modules.

8.4.2 Reference to overseas fire safety test outcomes

Currently, most BIPV modules are produced overseas and tested in accordance with overseas test methods. For example, if a BIPV module satisfies the requirements in accordance with EN 13501, it means the BIPV module is tested in accordance with ISO 11925-2 and EN 13823. In particular, ISO 11925-2:2020 provides that the information from these tests can be used to assess the hazard of ignition of PV/BIPV, while EN 13823 provides that the information from this test can be used to assess the probability of and consequences in the initial face of a fire (for instance, if BIPV/PV is close to a possible ignition source). As these tests are not recognised in Australia, the overseas certification of BIPV modules is not accepted in Australia. Therefore, overseas BIPV modules must be tested in accordance with Australian standards and demonstrate that the performance of BIPV module satisfies the Performance Requirements of the NCC. This creates hurdles for BIPV adoption in Australia, due to manufacturers' concerns about the cost of testing and the unclear size of the potential market. Furthermore, AS 5033 requires that PV modules must satisfy the test in accordance with UL 790, which provides the test results of fire spread and ignition for PV panels.

Although this test is related to PV products, this may also provide valuable references for fire safety engineers. As a pathway to evaluate Performance Requirements, Performance Solutions permit expert judgments as one of the assessment methods. In this process, the test results from international test methods may contribute to judging the fire hazard of BIPV modules in building elements. Therefore, it is important to explore whether and how test results from overseas can potentially contribute to professional judgment on Performance Solutions. In the future, Standards Australia could consider developing an Australian Standard specific to BIPV fire safety based on existing international standards in this area.

8.4.3 Relevant Deemed-to-Satisfy Provisions associated with BIPV

Deemed-to-Satisfy Provisions is one of the pathways to satisfy the Performance Requirements in the NCC. However, as a new technology, BIPV has not been considered in the current DtS Provisions, which means there are not any DtS Provisions that can deem the application of BIPV to satisfy the relevant Performance Requirements. Therefore, a future research direction is to consider drafting the relevant Deemed-to-Satisfy Provisions associated with BIPV, for submission to Australian Building Codes Board.

8.5 Section summary

This section has suggested 17 possible future research directions, which include (1) Mitigation of fire spread including vertical and lateral fire spread, the hazard of debris, the impact of building design strategies, and the mitigation of electric hazards; (2) Test configurations, including specimen size, active specimens in tests, toxic gas emissions, and suggestion for common structures of specimens; (3) Product innovation, focusing on the protection of electrical components and alternative materials for BIPV modules; and (4) Regulations, suggestions in relation to AS 5033, reference to overseas fire safety test outcomes, and relevant Deemed-to-Satisfy Provisions associated with BIPV.

Appendix A BIPV product performance review

The RMIT Solar Energy Application Lab has established a global BIPV product database with 218 PV products from 34 manufacturers. 27 manufacturers with 180 products provide brochures giving the relevant fire safety properties. As Figure A.1 shows, only one manufacturer uses EN 13501, four manufacturers use UL1703, while 22 manufacturers use IEC 61730.

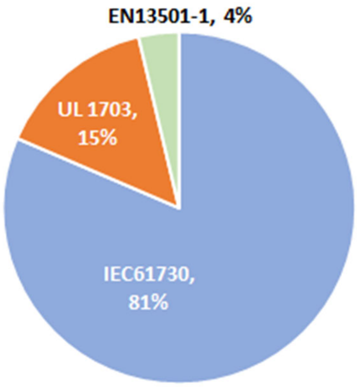

Figure A.1 Standards of fire classification of BIPV products by 27 manufactures

Table A.1 Fire performance criteria of different standards

Standard	Performance criteria
Class A (UL 1703: 2019)	Flame spread less than 6 ft. in 10 minutes
Class C (UL1703: 2019)	Flame spread less than 13 ft. in 4 minutes
Class B (EN 13501-1: 2018)	B: a) EN ISO 11925-2 Under condition of surface flame attack and, where required, edge flame attack with 30 s exposure time, there shall be no flame spread in excess of 150 mm vertically from the point of application of the test flame within 60 s from the time of application; b) EN 13823 No lateral flame spread (LFS) to the edge of the specimen. FIGRA (= FIGRA0,2 MJ) ≤ 120 W/s THR600s ≤ 7,5 MJ S2: EN 13823 The product shall satisfy all of the following criteria: SMOGRA ≤ 180 m2/s2 and TSP600s ≤ 200 m2. d0: if no flaming droplets/particles occur within 600 s when tested in accordance with EN 13823
IEC 61730: 2016	Refer to ISO 13501-5 or UL 1703

Appendix B Comparison of standards for building

Table B.1 Definition of Building Classification/Construction Type

Country	Building/Construction classification		Purpose of building	Building height	Material	Description
Australia (NCC Vol 1 A6)	Building classification	2	√	-	-	Two or more sole-occupancy units
		3				Residential building providing long-term or transient accommodation for a number of unrelated persons
		4				A dwelling in a Class 5, 6, 7, 8 or 9 building
		5				An office building used for professional or commercial purposes
		6				A shop or other building used for the sale of goods by retail or the supply of services direct to the public
		7				Storage-type building
		8				Process-type building
		9				Health care building / assembly building in school
	Construction type	Construction A	-	√	-	3 or more storeys of Class 2, 3, 9 & 4 or more storeys of Class 5, 6, 7, 8
		Construction B				2 storeys of Class 2, 3, 9 & 3 storeys of Class 5, 6, 7, 8
		Construction C				1 storey of Class 2, 3, 9 & 1-2 storeys of Class 5, 6, 7, 8
UK (Approved document B Section 0)	Building classification	1	√	-	-	Residential building (dwellings)
		2				Residential building (institutional/other)
		3				Office building
		4				Shop and commercial
		5				Assembly and recreation
		6				Industrial building
		7				Storage and other non-residential building

Country	Building/Construction classification		Purpose of building	Building height	Material	Description
US (NFPA 5000 Section 7.2)	Construction type	Type I	-	-	√	Fire-resistive: High-rise buildings made of concrete and protected steel
		Type II				Non-combustible: Newer buildings with tilt slabs or reinforced masonry walls and a metal roof.
		Type III				Ordinary: New or old buildings with non-combustible walls but a wood-framed roof.
		Type IV				Heavy Timber: Older buildings with thick lumber used for structural elements.
		Type V				Wood-framed: Many modern buildings with combustible framing and roofs.
Canada (National Building code of Canada Section 1.4)	Building classification	A1	√	-	-	Assembly occupancies intended for the production and viewing of the performing arts
		A2				Assembly occupancies not elsewhere classified in Group A
		A3				Assembly occupancies of the arena type
		A4				Assembly occupancies in which occupants are gathered in the open air
		B1				Detention occupancies
		B2				Treatment occupancies
		B3				Care occupancies
		C				Residential occupancies
		D				Business and personal services occupancies
		E				Mercantile occupancies
		F1				High-hazard industrial occupancies
		F2				Medium-hazard industrial occupancies
		F3				Low-hazard industrial occupancies

Country	Building/Construction classification		Purpose of building	Building height	Material	Description
China (GB 50016 Section 5.1)	Building classification	1	-	√	-	Residential building: Building height more than 54 m Public building: 1.Building height more than 50 m 2.Shopping centre, exhibition buildings, telecommunication buildings, post buildings, commercial buildings, and other multiple functions buildings that any floor area is more than 1000m2. 3.Health care buildings. 4.Provincial and above radio and television and disaster prevention command and dispatch building, network bureau level and provincial power dispatch building 5.Libraries and bookstores with over 1 million books
		2				Residential building: Building height more than 27 m but less than 54 m Public building: Other high-rise public buildings
		3				Residential building: Building height less than 27 m
		4				Residential building: Single storey building with more than 24 m height Public building: Other public buildings with less than 24 m height
Singapore (Fire code 2018 Section 1.4)	Building classification	I	√	-	-	Small residential building
		II				Other residential building
		III				Institutional building
		IV				Office

Country	Building/Construction classification		Purpose of building	Building height	Material	Description
		V				Shop
		VI				Factory
		VII				Place of public resort
		VIII				Storage and general

Table B.2 performance criteria of non-combustible building materials

Country	National Regulation/ Standard	Performance Criteria
Australia	AS 1530.1	Mean duration of sustained flaming should be zero
		Mean furnace thermocouple temperature rise should not exceed 50 °C
		Mean specimen surface thermocouple rise should not exceed 50 °C
UK	EN 13501-1	Gross heat of combustion (PCS) ≤ 3,0 MJ/kg
		Temperature rise (ΔT) ≤ 50 °C and mass loss (Δm) ≤ 50 % and duration of sustained flaming (t_f) ≤ 20s.
		Smoke growth rate (SMOGRA) and total smoke production within 600 s (TSP600s) shall be less than 30 m^2/s^2 and 50 m^2 respectively
		No flaming droplets in 600s
US	ASTM 136	Weight loss of test specimen is 50 % or less: The recorded temperatures of the surface and interior thermocouples do not at any time during the test rise more than 30°C (54°F) above the stabilized furnace temperature No flaming from the test specimen after the first 30
		Weight loss of the specimen exceeds 50 % The recorded temperature of the surface and interior thermocouples do not, at any time during the test, rise above the stabilized furnace temperature No flaming from the test specimen is observed at any time during the test

Countr y	National Regulation/ Standard	Performance Criteria
Canada	ULC-S135	Average total heat release (heat flux of 50 kW/m^2) is not more than 3 MJ/m^2
		Average smoke extinction area is not more than 1.0 m^2
China	GB 50016	As for the requirement in EN 13501-1
Singapore	BS 476 Part 4	a. any material of density 300 kg/m^3 or more, which when tested in accordance with BS 476: Part 11, does not flame, and the rise in temperature on the furnace thermocouple is not more than 20°C; b. any material with a non-combustible core at least 8mm thick having combustible facings (on one or both sides) not more than 0.5mm thick; and c. any material of density less than 300 kg/m3, which when tested in accordance with BS 476: Part 11, (1) does not flame for more than 10 sec; (2) the rise in temperature on the centre (specimen) thermocouple is not more than 35°C; and (3) the rise in temperature on the furnace thermocouple is not more than 25°C.

Table B.3 Performance criteria for fire reaction of external walls

Country	National Regulation	Standard Referred	Classification criteria
Australia	NCC 2019	AS 5113	Temperature 4 m (refer to ISO 13785) or 5 m (refer to BS 8414) above the opening measured 10 mm refer to (ISO 13785) or 50 mm (refer to BS 8414) from the exposed specimen face shall not exceed 600 °C for a continuous period greater than 30 s.
			Temperature at the mid-depth of each combustible layer or any cavity 4 m (refer to ISO 13785) or 5 m (refer to BS 8414) above the opening shall not exceed 250 °C for a continuous period greater than 30 s.
			Where the system is attached to a wall that is not required to have an FRL of -/30/30 or 30/30/30 or more, the temperature on the unexposed face of the specimen 900 mm above the opening shall not exceed a 180 K rise. Five thermocouples equally spaced at 500 mm centres with insulating pads, fitted in accordance with the requirements of AS 1530.4 for the measurement of surface temperatures shall be used.
			Where the system is attached to a wall that is not required to have an FRL of -/30/30 or 30/30/30 or more, flaming or the occurrence of openings in the exposed face of the specimen above the opening shall not occur.
			Flame spread beyond the confines of the specimen in any direction, as determined during the post-test examination, shall not occur; the examination shall include flame damage such as melting, charring but not smoke discolouration or staining of the surface, any intermediate layers and the cavity.
			Continuous flaming on the ground for more than 20 seconds from any debris or molten material from the specimen shall not occur.
			The total mass of debris falling in front of the specimen shall not exceed 2 kg. The mass shall be measured after the end of the test.

<table>
<tr><th>Country</th><th>National Regulation</th><th>Standard Referred</th><th colspan="3">Classification criteria</th></tr>
<tr><td rowspan="4">UK</td><td rowspan="4">Approved Document B</td><td rowspan="4">EN 13501</td><td colspan="3">Under condition of surface flame attack and, where required, edge flame attack (see 6.3) with 30 s exposure time, there shall be no flame spread in excess of 150 mm vertically from the point of application of the test flame within 60 s from the time of application</td></tr>
<tr><td colspan="3">No lateral flame spread (LFS) to the edge of the specimen.</td></tr>
<tr><td colspan="3">FIGRA (= FIGRA0,2 MJ) ≤ 120 W/s</td></tr>
<tr><td colspan="3">THR600s ≤ 7,5 MJ</td></tr>
<tr><td rowspan="4">US</td><td rowspan="4">NFPA 5000</td><td rowspan="4">NFPA 285</td><td rowspan="3">Flame propagation of exterior face of test specimen</td><td rowspan="3">Flame propagation on the exterior face of the test specimen shall not occur either vertically or horizontally beyond the area of fame plume impingement by the window burner fames.</td><td>A temperature of 538°C is measured by any one of the thermocouples numbers 1 1 and 14 through 17</td></tr>
<tr><td>Flames emitting from the surface of the exterior face of the test specimen reach a height of 3.05 m or greater above the top of the window opening</td></tr>
<tr><td>Flames emitting from the surface of the exterior face of the test specimen reach a horizontal distance of 1.52 m or greater from the vertical centreline of the window opening</td></tr>
<tr><td>Vertical flame propagation of combustible</td><td>Greater than 6.4 mm thick containing combustible components</td><td>Temperatures in the combustible components shall not exceed 417°C above their temperature as measured immediately after the start of the test by thermocouple nos. 28 and 31 through 40</td></tr>
</table>

Country	National Regulation	Standard Referred	Classification criteria		
			components and insulation	Constructed of exterior wall panels containing combustible components and having a wall cavity with an air space	Temperatures in the wall cavity air space shall not exceed 538°C as measured by thermocouples nos. 28 and 31 through 40
					Temperatures in the wall cavity and stud cavity insulation shall not exceed 417°C above their temperature as measured immediately after the start of the fire test by thermocouples nos. 55 through 65 and 68 through 79
				6.4 mm thick or less containing combustible components and having a wall cavity without an air space	temperatures in the wall cavity and stud cavity insulation shall not exceed 417°C above their temperature as measured immediately after the start of the fire test by thermocouples nos. 28, 31 through 40 and 55 through 65
				Constructed of non-combustible or limited-combustible exterior wall panels and having a wall cavity with an air space	Temperatures in the wall cavity air space shall not exceed 538°C as measured by thermocouples nos. 28 and 31 through 40
					Temperatures in the wall cavity and stud cavity insulation shall not exceed 417°C above their temperature as measured immediately after the start of the fire test by thermocouples nos. 55 through 65 and 68 through 78

Country	National Regulation	Standard Referred	Classification criteria		
			Horizontal flame propagation of combustible components and insulation	Greater than 6.4 mm thick containing combustible components	temperatures in the combustible components shall not exceed 417°C above their temperature measured immediately after the start of the fire test by thermocouples nos. 18 and 19
				Constructed of exterior wall panels containing combustible components and having a wall cavity with an air space	Temperatures in the wall cavity air space shall not exceed 538°C as measured by thermocouples nos. 18 and 19
					Temperatures in the wall cavity and stud cavity insulation shall not exceed 417°C above their temperature as measured immediately after the start of the fire test by thermocouples nos. 66, 67, 79, and 80
				6.4 mm thick or less containing combustible components and having a wall cavity without an air space	temperatures in the wall cavity and stud cavity insulation shall not exceed 750°F (417°C) above their temperature as measured immediately after the start of the test by thermocouples nos. 18, 19, 66, and 67
				Constructed of non-combustible or limited-combustible exterior wall panels and having a wall	Temperatures in the wall cavity air space shall not exceed 538°C as measured by thermocouples nos. 18 and 19

Country	National Regulation	Standard Referred	Classification criteria		
				cavity with an air space	Temperatures in the wall cavity and stud cavity insulation shall not exceed 417°C above their temperature as measured immediately after the start of the fire test by thermocouples nos. 66, 67, 79, and 80
			Temperatures in second-story test room	Temperatures measured 25 mm from the interior surface of the test specimen within the second-story test room shall not exceed 278°C above the ambient air temperature of the test facility at the start of the fire test as measured by thermocouples nos. 49 through 54	
			Flames in second-story test room	Flames shall not occur in the second-story test room.	
			Flame propagation to adjacent horizontal spaces	Flames shall not occur beyond the intersection of the test specimen and the side walls of the test apparatus	
Canada	National Building Code of Canada	CAN/ULC-S134	The flaming spread of BIPV external wall should be not more than 2 m above the opening		
			The heat flux during the flame exposure on the wall is not more than 25 kW/m2 at 3.5 m above the opening		
Singapore	Fire code 2018	EN 13501	Same as the UK requirement.		

Note: 1. The values of 4 m and 10 mm are criteria based on the test of ISO 13785, and the values of 5 m and 50 mm are criteria based on the test of BS 8414.

Table B.1 Fire resistance of non-loadbearing external walls in Australia (National Construction Code 2019)

Building element	Distance from fire source	Class 2,3, or 4	Class 5,7a, or 9	Class 6	Class 7b or 8
Type A	less than 1.5 m	-/90/90	-/120/120	-/180/180	-/240/240
	1.5 to less than 3 m	-/60/60	-/90/90	-/180/120	-/240/180
Type B	less than 1.5 m	-/90/90	-/120/120	-/180/180	-/240/240
	1.5 to less than 3 m	-/60/30	-/90/60	-/120/90	-/180/120
Type C	less than 1.5 m	90/90/90	90/90/90	90/90/90	90/90/90
	1.5 to less than 3 m	-/-/-	60/60/60	60/60/60	60/60/60

Table B.2 Fire resistance of non-loadbearing external walls in the UK (Approved Document B)

Building element	Requirements					
Height		Up to 5m	Up to 11m	Up to 18m	Up to 30m	More than 30m
Residential building	Without sprinkler	EI[15] 30	EI 60	Not permitted[16]	Not permitted	Not permitted
	With sprinkler[17]	EI 30	EI 60	EI 60	EI 90	EI 120
Office building	Without sprinkler	EI 30	EI 60	EI 60	EI 90	EI 120
	With sprinkler	EI 30	EI 30	EI 30	EI 60	EI 120
Commercial	Without	EI 60	EI 60	EI 60	EI 90	Not

[15] 'EI' means integration and insulation.
[16] 'Not permitted' means the purpose group requires sprinkler where there is a specific height requirement of top storey above ground level.
[17] With sprinkler system' means that the building is fitted throughout with an automatic sprinkler system.

building	sprinkler					permitted
	With sprinkler	EI 30	EI 60	EI 60	EI 60	EI 120
Industrial building	Without sprinkler	EI 60	EI 90	EI 90	EI 120	Not permitted
	With sprinkler	EI 30	EI 60	EI 60	EI 60	EI 120
Storage building	Without sprinkler	EI 60	EI 90	EI 90	EI 120	Not permitted
	With sprinkler	EI 30	EI 60	EI 60	EI 60	EI 120
Health care or school	Without sprinkler	EI 60	EI 60	EI 60	EI 90	Not permitted
	With sprinkler	EI 30	EI 60	EI 60	EI 60	EI 120

Table B.3 Fire resistance of non-loadbearing external walls in the USA (NFPA 5000)

Occupancy Classification	Horizontal Separation			
	0-1.5 m	1.5-3 m	3-9 m	> 9 m
Assembly, educational, day care, healthcare, ambulatory health care, detention and correctional, residential, residential board and care, business, industrial, and storage occupancies with low hazard contents	1 h	1 h	0	0
Mercantile and indust1ial and storage occupancies with ordinary hazard contents	2 h	1 h	0	0
Industrial and storage occupancies with high hazard contents exceeding the MAQ[18] per control area as set forth in 34.1.3 and complying with Protection Level 4 or Protection Level 5	3 h	2 h	1 h	0

[18] MAQ means Maximum allowable quantity

Table B.4 Fire resistance of non-loadbearing external walls in China (GB 50016, 2019)

	Class 1	Class 2	Class 3	Class 4
Non-loadbearing external wall	1 h	1 h	0.5 h	0

Table B.5 Fire resistance of non-loadbearing external walls in Singapore (Fire code 2018) – buildings other than single- storey buildings

Purpose Group	Maximum Dimensions			Minimum period of fire resistance for elements of structure/external wall/compartment wall forming part of:	
	Height (m)	Floor Area (m^2)	Cubical Extent (m^3)	Above ground Storey (hrs)	Basement Storey (hrs)
PG I - Small residential					
House having not more than 3 storeys	NL[1]	NL	NL	1	1
House having 4 storeys	NR[2]	250	NR	1	1
	NL	NL	NL	1	2
House having more than 4 storeys	NL	NL	NL	1	2
PG II - Other residential					
Building or part (+) having not more than 2 storeys	NL	500	NR	1	1
	NL	NL	NL	1	2
Building or part (+) 3 storeys	NR	250	NR	1	1
	NL	NL	NL	1	2
	28	3000	8500	1	2

Purpose Group	Maximum Dimensions			Minimum period of fire resistance for elements of structure/external wall/compartment wall forming part of:	
Building having more than 3 storeys	NL	NL	NL	2	2
PG III – Institutional	28	2000	NL	1	1
	NL	NL	NL	2	2
PG IV – Office	15	NL	3500	1	1
	28	5000	14000	1	2
	NL	NL	NL	2	2
PG V – Shop	15	NR	3500	1	1
	28	1000	7000	1	2
	NL	NL	NL	2	4
PG VI - Factory	15	NR	4250	1	1
	28	NR	8500	1	2
	NL	NL	NL	2	4
PG VII - Place of public resort	15	NR	3500	1	1
	28	1000	7000	1	2
	NL	NL	NL	2	2
PG VIII - Storage and general	15	NR	1700	1	1
	15	NR	3500	1	2
	28	NR	7000	2	4
	NL	NL	NL	4	4

Notes: 1. "NL" means No limit applicable.

2. "NR" means Not Relevant.

Table B.6 Fire resistance of non-loadbearing external walls in Singapore (Fire code 2018) - single storey buildings

Purpose Group	Maximum Floor Area (m^2)	Minimum period of fire resistance for elements of structure, external wall/compartment wall (hrs)
PG I - Small residential	NL	1
PG II - Other residential	NL	1
PG III - Institutional	NL	1
PG IV - Office	NL	1
PG V - Shop	3000	1
	NL	2
PG VI - Factory	3000	1
	NL	2
PG VII - Place of public resort	3000	1
	NL	2
PG VIII - Storage and general	1000	1
	3000	2
	NL	4

Table B.7 Performance requirements of roofs/skylights

Country	Structure	National regulation	Standard referred	Performance requirement
Australia	Roof	National Construction Code	-	-
	Skylight		AS 1530.3	Index of 9 for spread of flame; Index of 8 for smoke developed; For type A construction, skylights should be not less than 3 m from any boundary and any part of the building above the roof.
UK	Roof	Approved Document B	-	-
	Skylight		EN 13501-5	No penetration of roof system within 1 h; In preliminary test, after withdrawal of the test flame, specimen burn is less than 5 min Flame spread is less than 0.38 m across region of burning
US	Roof	NFPA 5000	UL 1703	Class B: flame spread less than 2.4 m in 10 mins; Class C: flame spread less than 4 m in 4 mins; not less than 15 m from HC fire wall.
	Skylight		NFPA 5000	In Type I and Type II constructions, skylight frames shall be constructed of non-combustible materials not less than 7.62 m from HC fire wall.
			UL 1703	Class B burning brand

Country	Structure	National regulation	Standard referred	Performance requirement
Canada	Roof	National Building Code of Canada	UL 1703	Class C: flame spread less than 4 m in 4 mins
	Skylight		-	Flame spread rating not more than 150/75
Singapore	Roof	Fire code 2018	ASTM E108	The surface of materials for roof covering and roof construction shall have a surface spread of flame rating not lower than Class 1, or Class A when tested in accordance with ASTM E108, except in the case of PG I and PG II, and in buildings that are protected throughout with automatic sprinkler systems Combustible material can be used for roof construction for PG III, IV, V and VII buildings which satisfy the following requirements: a. the building shall not exceed four storeys; b. the roof space between the roof and the ceiling shall be sub-divided by cavity barriers where required to comply with the relevant provisions of concealed spaces, and openings in cavity barriers shall be fire-stopped to comply with the requirements of fire stopping; and c. if the underside of the roof serves as the ceiling to a room or space, the elements of the underside of the roof shall comply with the relevant provisions of classification of spread of flame for restriction of spread of flame.

Table B.8 Roof covering classifications in the USA (NFPA 5000)

Type of Construction		Minimum Roof Covering Classification
Type I	442	B
	332	B
Type II	222	B
	111	B
	000	C
Type III	211	B
	200	C
Type IV	2HH	B
Type V	111	B
	000	C

Table B.9 Fire resistance of roofs in Australia (National Construction Code 2019)

Building Classification	Rise in Storeys	Type of construction	Roof
Class 2 & 3 (Residential Building)	3	A	90/60/30
	4 or more	A	90/60/30
Class 5 (Office Building)	4 or more	A	120/60/30
Class 6 (Commercial Building)	4 or more	A	180/60/30
Class 7a (Carpark)	4 or more	A	120/60/30
Class 7b (Storage Building)	4 or more	A	240/90/60
Building 8 (Industrial Building)	4 or more	A	240/90/60
Building 9 (Health Care or School)	3	A	120/60/30
	4 or more	A	120/60/30

Table B.10 Fire resistance of roofs in the USA (NFPA 5000)

	Type I			Type II		Type III		Type IV	Type V	
Roof	442	332	222	111	000	211	200	2HH	111	000
	2	1.5	1	1	0	1	0	H	1	0

Table B.11 Performance requirements of windows and other openings

Country	National Regulation	Performance requirement	
Australia	NCC 2019	Distance from boundary	3 m from a side or rear boundary of the allotment
			6 m from the far boundary of a road, river, lake or the like adjoining the allotment
			6 m from another building on the allotment
		Vertical separation	In the Type A construction, if any part of a window or other opening in an external wall is above another opening in the storey next below and its vertical projection falls no further than 450 mm outside the lower opening (measured horizontally), the openings must be separated unless the building has a sprinkler system.

<table>
<tr><th>Country</th><th>National Regulation</th><th colspan="2">Performance requirement</th></tr>
<tr><td rowspan="4">UK</td><td rowspan="4">Approved Document B</td><td rowspan="4">Fire reaction (window spandrels and infill panels)</td><td>PCS ≤ 3,0 MJ/kg</td></tr>
<tr><td>ΔT ≤ 50 °C and Δm ≤ 50 % and tf ≤ 20s.</td></tr>
<tr><td>SMOGRA and TSP600s shall be less than 30 m2/s2 and 50 m2 respectively</td></tr>
<tr><td>No flaming droplets in 600s</td></tr>
<tr><td rowspan="4">US</td><td rowspan="4">NFPA 5000</td><td>Horizontal distance and area</td><td>If the exterior wall has a requirement of fire resising, the horizontal distance and area of opening in the exterior wall shall not exceed that permitted in terms of the requirement of Maximum area of exposed building face in NFPA 5000 Section 7.35</td></tr>
<tr><td>Unprotected openings</td><td>The area of unprotected openings in an exterior wall shall be expressed as a percentage in terms of the requirement of Maximum area of exposing building face in NFPA 5000 Section 7.35</td></tr>
<tr><td rowspan="2">Vertical separation</td><td>For a building which has four or more stories and is not protected with a fire sprinkler system, NFPA requires a vertical separation for exterior openings if the opening is located within a 1525 mm radius of the next story above.</td></tr>
<tr><td>The opening should be separated by a spandrel panel which is not less than 915 mm high or a wall with a one-hour fire resising rating. Horizontally, protection is provided via a 760 mm horizontal barrier with a one-hour fire resising rating.</td></tr>
<tr><td rowspan="2">Canada</td><td rowspan="2">National Building Code of Canada</td><td>Unprotected openings</td><td>Not be installed higher than the second storey if there is not any other protection measure</td></tr>
<tr><td>Vertical glazing</td><td>Combustible vertical glazing installed no higher than the second storey and have a flame-spread rating not more than 75
The flame-spread rating of combustible glazing is permitted to be not more than 150 if the aggregate area of glazing is not more than 25% of the wall area of the storey in which it is located, and
a) the glazing is installed in a building not more than 1</td></tr>
</table>

Country	National Regulation		Performance requirement
			storey in building height, b) the glazing in the first storey is separated from the glazing in the second storey for opening protection, or c) the building is sprinklered throughout.
China	GB 50016	Vertical separation	A vertical separation should be set if the vertical distance between openings is less than 1.2 m. If there is a sprinkler system, the requirement of vertical distance is 0.8 m

Table B.12 Performance requirements of ancillary elements/attachments

Country	National Regulation	Performance requirement
Australia	NCC 2019	Non-combustible
		Not reduce requirement of FRL for the external wall that is attached or fixed
		Index of 9 for spread of flame; Index of 8 for smoke developed;
UK	Approved Document B	Used on all types of buildings except 'Relevant buildings'
		Canopy could be exempt from building regulations if the canopy is attached to the side of a building and the edges of the canopy are a minimum of 2 m from the relevant boundary
US	NFPA 5000	In Type I and Type II constructions, the frames shall have one-hour fire-resistance-rated construction with non-combustible covers
		Permit to have a combustible covering that meets: flame spread index 0-25; smoke developed index 0-450.
Canada	National Building Code of Canada	Permitted to be used if the building: is not more than 3 storeys in building height, or has a sprinkler system
China	GB 50016	The material of attachment should be non-combustible, except: if the building height is not more than 50 m, the material can be B

Country	National Regulation	Performance requirement
Singapore	Fire code 2018	The outer layers shall be constructed of non-combustible material. The composite panel used for external wall cladding shall be mounted against a 1-hr fire-rated wall and shall comply with any of the following: (1) Its core material shall meet at least: (a) BS 476 Pt 4, or (b) BS 476 Pt 11, or (c) Class 0 flame-spread rating when tested in accordance with BS 476 Pt 6 & 7, or (d) Class B classified under EN 13501-1. (2) The panel assembly shall comply with NFPA 285.

Appendix C Standards referenced in this report

AS 1530.1 Methods for fire tests on building materials, components and structures Part 1: Combustibility test for materials

AS 1530.3 Methods for fire tests on building materials, components and structures Part 3: Simultaneous determination of ignitability, flame propagation, heat release and smoke release

AS 1530.4 Methods for fire tests on building materials, components and structures Part 4: Fire-resistance tests for elements of construction

AS/NZS 3000 Electrical installations

AS/NZS 3013 Electrical installations. Classification of the fire and mechanical performance of wiring system elements

AS/NZS 3820 Essential safety requirements for electrical equipment

AS/NZS 5033 Installation and safety requirements of photovoltaic arrays

AS 5113 Classification of external walls of buildings based on reaction-to-fire performance

ASTM 136 Standard Test Method for Assessing Combustibility of Materials Using a Vertical Tube Furnace at 750°C

ASTM E108 Standard Test Methods for Fire Tests of Roof Coverings

BS 476-6 Fire tests on building materials and structures — Part 6: Method of test for fire propagation for products

BS 476-7 Fire tests on building materials and structures Part 7. Method of test to determine the classification of the surface spread of flame of products

BS 476-11 Fire tests for assessing the heat emission from building materials

BS 476:20-23 Fire Resistance Test to Building Material

BS 8414-2:2020 Part 2: Test method for non-loadbearing external cladding systems fixed to, and supported by, a structural steel frame

CAN/ULC-S134 Standard Method of Fire Test of Exterior Wall Assemblies

EN 1182 Reaction to fire tests for products — Non-combustibility test

EN 11925-2 Reaction to fire tests - Ignitability of products subjuected to direct impingement of flame - part 2 Single-flame source test

EN 13823 Reaction to fire tests for building products — Building products excluding floorings exposed to the thermal attack by a single burning item

EN 1716 Reaction to fire tests for products - Determination of the gross heat of combustion (calorific value)

EN 13501-1 Fire classification of construction products and building elements - Part 1: Classification using data from reaction to fire tests

EN 13501-2 Fire classification of construction products and building elements – Part 2: Classification using data from fire resistance tests, excluding ventilation services

EN 13501-5 Fire classification of construction products and building elements. Classification using data from external fire exposure to roof tests

EN 50583-1 Photovoltaics in building- part 1: PV modules

GB/T 14402 Reaction to fire test for building materials and products-Determination of the heat of combustion

GB/T 20047.1 Photovoltaic (PV) module safety qualification. Part 1: Requirements for construction

GB/T 20284 Single burning item test for building materials and products

GB/T 51368 Technical standard for photovoltaic system on building

GB/T 8626 Test method of flammability -Building materials

GB/T 9535 Crystalline silicon terrestrial photovoltaic(PV) modules-design qualification and type approval

GB/T 9978-1 Fire-resistance tests-Elements of building construction-part1:General requirements

IEC 61215-2 Terrestrial photovoltaic module - Design qualification and type approval

IEC 61730-2 Photovoltaic (PV) module safety qualification

IEC 62980: Photovoltaic modules for building curtain wall applications

IEC 63092-1 Photovoltaics in buildings – Part 1: Requirements for building-integrated photovoltaic modules

ISO 13785-2 Reaction-to-fire tests for façades — Part 2: Large-scale test

ISO/TS 18178: Glass in building - Laminated solar photovoltaic glass for use in buildings

NFPA 285 Standard Fire Test Method for Evaluation of Fire Propagation Characteristics of Exterior Wall Assemblies Containing Combustible Components

NFPA 70 Article 690 Solar Photovoltaic (PV) Systems

SS 601-1 Photovoltaic (PV) systems – Requirements for testing, documentation and maintenance – Part 1: Grid connected systems – Documentation, commissioning tests and inspection

SS 638 Code of Practice of Electrical Installations

UL 1703 Standard for Flat-Plate Photovoltaic Modules and Panels

UL 263 Fire Tests of Building Construction and Materials

UL 790 Standard Test Methods for Fire Tests of Roof Coverings

ULC-S135 Standard test method for the determination of combustibility parametres of building materials using an oxygen consumption calorimeter (cone calorimeter)

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