Solar Energy Application Lab,
School of Property, Construction
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Red Fire Engineers

Fire Safety Requirements of Applying BIPV in Australia

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Executive Summary

This report focuses on the fire safety requirements applied to BIPV used as part of façades and roof, determined by the National Construction Code (NCC) and associated Australian Standards for building Classes 1 to 9. The fire tests are required to demonstrate compliance with the NCC. This study states the basic knowledge of BIPV application, and the analysis of fire risk based on the cases from Australia and overseas. According to the international standards relevant to the fire safety of BIPV applications, six tests are listed in the study, which contributes to satisfying the requirements for fire safety when BIPV is used as part of building envelopes. Although the Building Code of Australia does not have Deemed-to-Satisfy Provision for installation of BIPV on the façade and the roof of most buildings in the current stage, CP2 and CP4 in NCC provide the relevant Performance Requirements. Moreover, when BIPV is applied in building Types A and B (typically multi-residential buildings or other buildings with more than two storeys), the following Deem-to-Satisfy Provisions in the BCA must be considered, including C1.9(a)(i), C1.14(a), C2.6, C2.12, and C2.4 Specification C1.1. Meanwhile, several Australian Standards can be used to evaluate the performance of BIPV at high temperature, including (i) AS 1530.4:2014; and (ii) AS 5113:2016. In addition, the installation and safety requirements for PV arrays listed in the Australian Standard AS/NZS 5033:2014 Amendment No. 1 and 2 must also be met.

1. Research aims and scope

This report aims to provide an understanding of the following aspects:

- The fire safety requirements are applicable to BIPV used as part of façade and roofs, which are determined by the National Construction Code (NCC) and associated Australian Standards for building Classes 1 to 9.
- Fire tests that are required to demonstrate compliance with the NCC.

The following aspects will not be considered in this report:

- Mechanical resistance and stability of the BIPV module and system.
- Hygiene, health and the environment.
- Safety in use.
- Protection against noise.
- Energy economy and heat retention.
- Sustainable use of natural resource.
- Electrical properties (other than as a possible ignition source).

2. The application of BIPV in buildings

Building-integrated photovoltaic (BIPV) is a solar system used as building components for façade and roofs. BIPV can be used in buildings to replace the traditional façade or external wall materials such as stone, glass, and metal. Unlike building-added photovoltaic system (BAPV), which is an independent component to buildings, BIPV can be used during the construction process and can be used in both new or existing buildings.

The successful application of BIPV in a building can be seen from Figures 1 to 3, including the Federation of Korean Industries buildings and the application of PV façade in the airport terminal of Bari Palese. Figure 1 also shows that the BIPV would be best used in the southeast and southwest faces (highlighted in yellow colour) of the building.

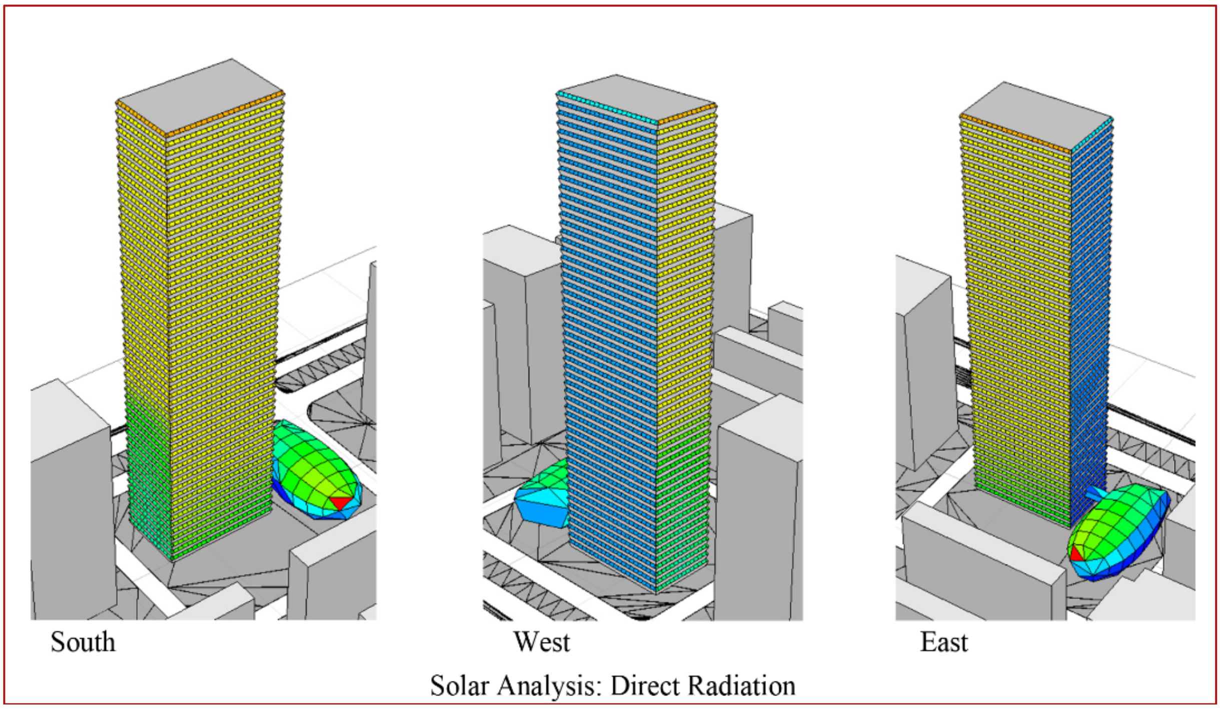

Figure 1: Federation of Korean Industries (FKI) (Betancur, 2017)

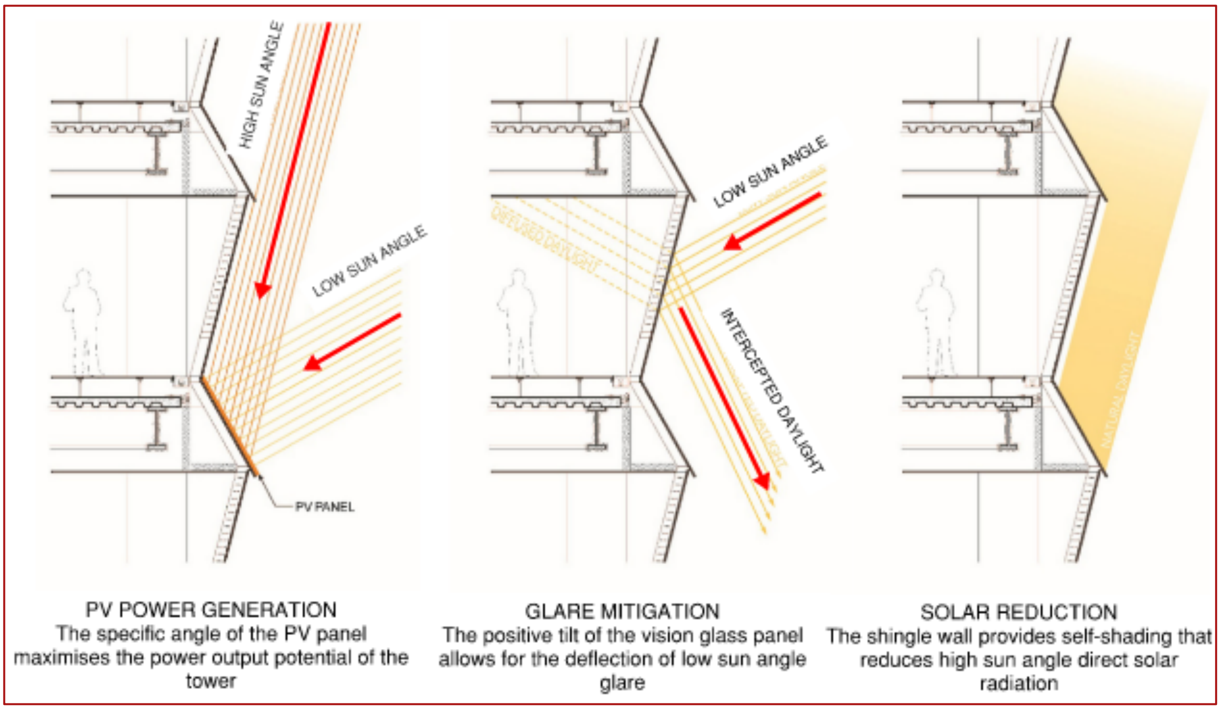

Figure 2: Location of solar panels on buildings (Betancur, 2017)

Figure 3: PV façade of the airport terminal of Bari Palese (Mazziotti et al., 2016)

Fire risks associated with solar panels in Australia

According to the report 'Fire Safety of Solar Photovoltaic Systems in Australia' by the Alternative Technology Association (ATA), data containing solar panel-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). This data shows a total of 400 recorded fires involving solar PV arrays and associated equipment from 2009 to 2015. A majority of these fires were reported in NSW, as shown in Figure 4 (ATA, 2016).

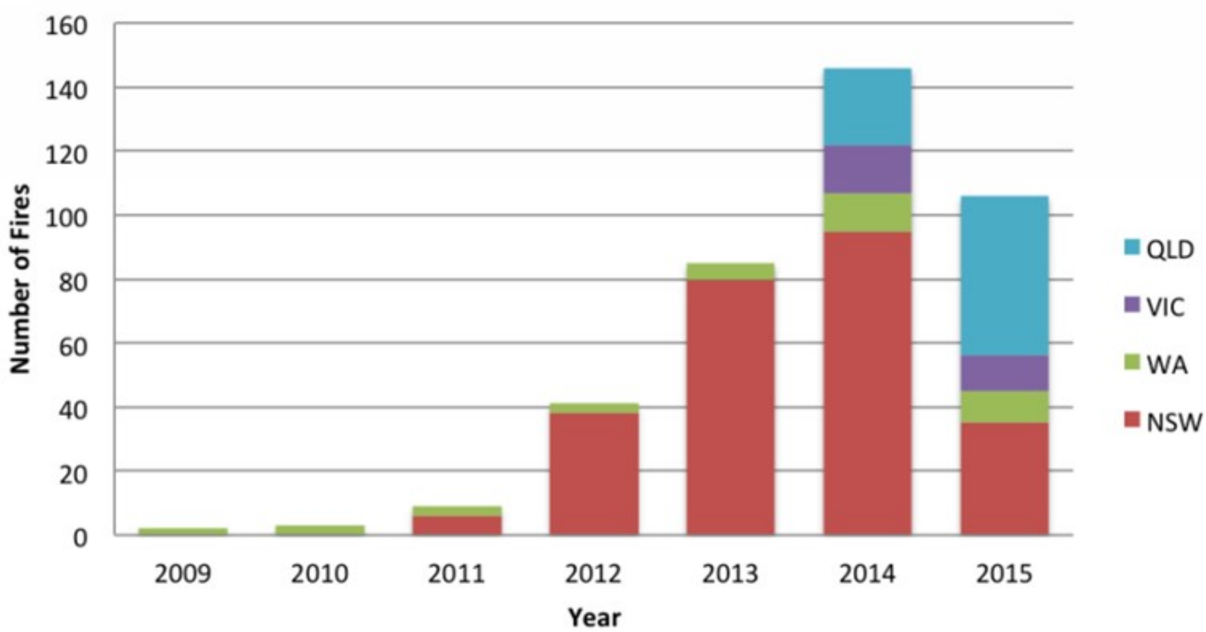

Figure 4: Solar panel-related fires in the different Australian States from 2009 to 2015 (ATA, 2016)

Figure 4 shows a steady increase in the number of solar panel-related fires from 2009 to 2015 out of 1.5 million installations in Australia (ATA, 2016). While the number of solar panel-related fires in QLD increased between 2014 to 2015, it slightly decreased in VIC. This number increased gradually in NSW from 2011 to 2014, then dropped by more than 50% in 2015. In general, the number of solar panel-related fires in Australia increased significantly in 2014. Although it slightly reduced in 2015, the number of solar-panel fires in 2015 was still higher than that occurred in the years from 2009 to 2013.

Data from AFAC provided causes of solar panel-related fires for each state. The causes were categorised into ten different types, as shown in Figure 5.

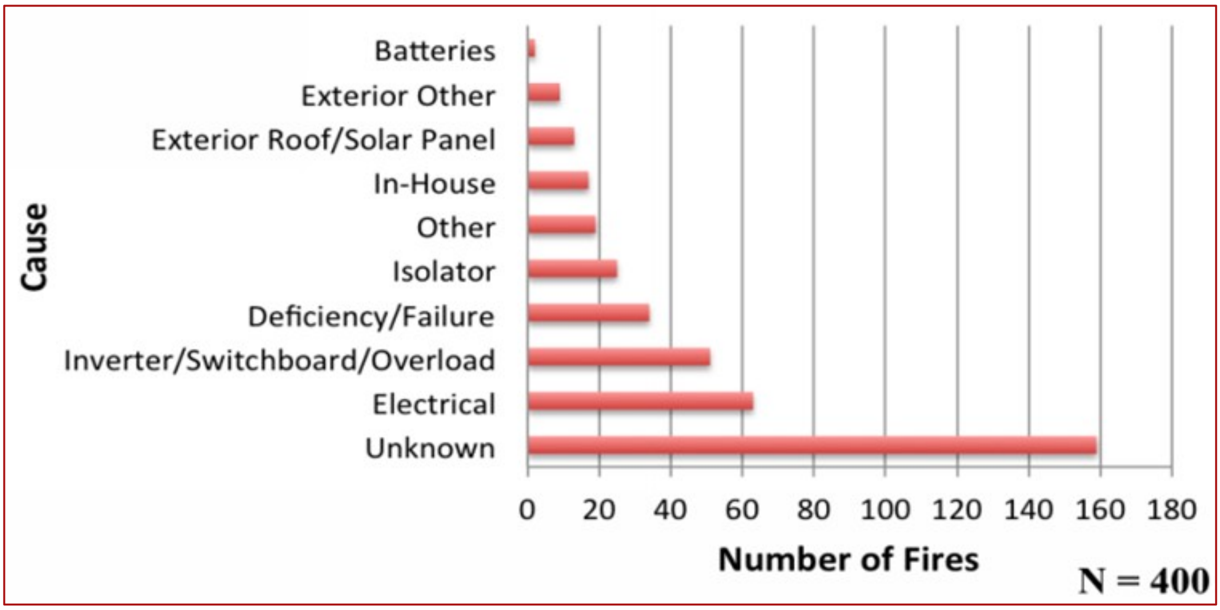

Figure 5: Causes of solar panel-related Fires in Australia, 2009 to 2015 (ATA, 2016)

Approximately 40% of the fires recorded from 2009 to 2015 had unknown causes. The next largest percentage cause of solar panel-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).

The data from Western Australia in the AFAC report provides a definite set of causes from thirty-eight of the recorded solar panel-related fires from 2009 to 2015. This is shown in Figure 6.

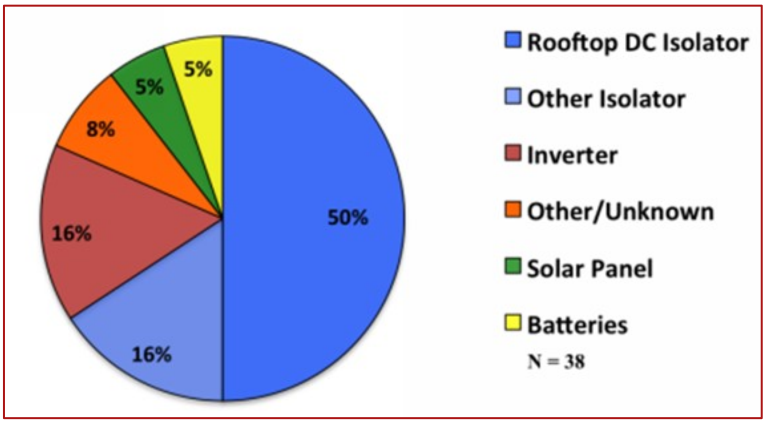

Figure 6: Causes of solar panel-related fires in Western Australia, 2009 to 2015 (ATA, 2016)

Six leading causes of fire in Western Australia was detected, including rooftop DC isolator, other isolators, inverter, other/unknown reason, solar panel and batteries from 2009 to 2015. Among these causes, 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 solar panel and batteries were the least common with only 5% each.

In NSW, Fire and Rescue New South Wales (FRNSW) recorded 221 solar panel-related fires from 2011 to 2015, as shown in Figure 7.

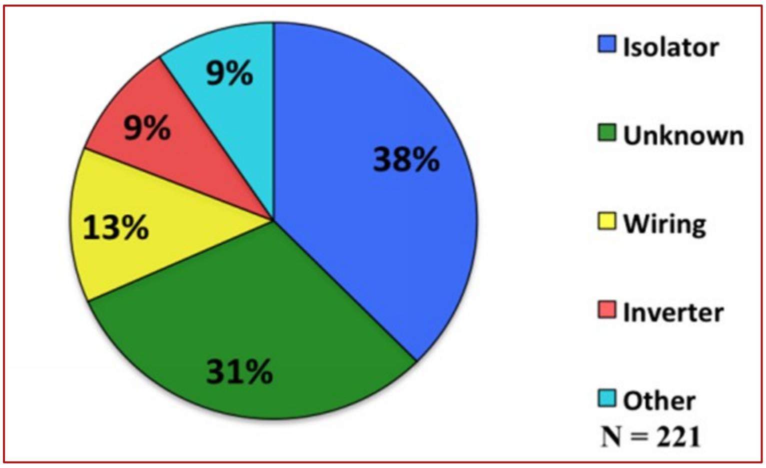

Figure 7: Causes of solar panel-related Fires in New South Wales, 2011 to 2015 (ATA, 2016)

Of the 221 recorded solar panel-related fires, 38% were caused by the Isolator, and 31% were unknown (ATA, 2016).

Based on the data of related incidents in Australia, there have been no deaths or injuries that were associated with solar panel-related fires.

International fire incidents related to solar panel

The subsequent sections identify the locations and recorded causes of solar panel-related fires outside Australia. Based on the available data and associated reporting, there have been no deaths or injuries that were associated with solar panel-related fires.

Bakersfield, California USA, April 2009

A fire occurred on the roof of a retail store (Target) at Bakersfield, California. The store had a 383 kW solar PV system array on the roof. The fire started in two locations with causes associated with a ground fault [1].

Mount Holly, North Carolina USA, April 2011

A fire occurred on the roof of the National Gypsum Company, a drywall manufacturer, at Mount Holly, North Carolina [2]. The cause of the fire was reportedly related to a ground fault [1].

Goch, Germany, 2012

A fire occurred in an area of approximately 4,000 m^2 warehouse at Goch, Germany, and the cause of the fire was reportedly associated with a technical defect in the photovoltaic system [3].

Lafarge, Wisconsin USA, May 2013

A fire occurred in the corporate headquarters of Organic Valley at Lafarge, Wisconsin [3,4]. The roof of the building was constructed of lightweight wooden trusses with standing seam metal roof panels fastened to the trusses. The building was protected by an automatic wet-pipe fire sprinkler system, and the attic was protected by a dry-pipe sprinkler system.

The fire started inside the building and spread to a concealed attic space [4]. The building's concealed spaces were insulated with a recycled cotton-based denim material that was rapidly consumed by the growing fire, which eventually spread into an attic space. The building's pitched roof structure was covered with arrays of photovoltaic (PV) panels that made vertical ventilation of the attic space by the firefighters nearly impossible.

The sprinkler system was not effective in extinguishing the fire. At some point during fire development, the metal roof was energised, which inhibited fire brigade intervention.

Delanco, New Jersey USA, September 2013

A fire occurred in the Dietz and Watson Warehouse at Delanco, New Jersey [3]. The building was approximately 28,000 m^2 and over 7,000 solar PV modules were installed on the roof.

Reportedly, unprotected combustible roofing was a fuel source and allowed the fire to spread. The large solar PV array on the roof reportedly inhibited the ability of firefighters to suppress the fire.

1 http://www.solarabcs.org/about/publications/reports/blindspot/pdfs/BlindSpot.pdf
2 http://www.wbtv.com/story/14461049/solar-panals-catch-fire-on-factory-rooftop-puzzling-investigators
3 Wills et al. Commercial Roof Mounted PV System Installation Best Practices Review and All Hazard Assessment, 2014.
4 http://www.nfpa.org/newsandpublications/nfpa-journal/2014/january-february-2014/features/perfect-storm

The fire burned for 24 hours before it could be suppressed, and it consumed the entire building and its contents.

3. Safety requirements by BCA and Australian Standards

In Australia, the application of BIPV must not adversely affect the fire and life safety requirements for occupants, firefighters, and buildings. This is legislated in the Building Code of Australia (BCA).

In the BCA, there are three types of fire-resisting construction, namely Type A, Type B and Type C. Type A construction is the most fire-resistant type of construction, while Type C construction is the least fire-resistance and Type B construction falls between these two. The types of construction are determined by the use (building classification) and the rise in storeys, as shown in Table 1.

Table 1: Types of construction (ABCB, 2019)

Rise in storeys	Class of building (2, 3, 9)	Class of building (5, 6, 7, 8)
4 or more	A	A
3	A	B
2	B	C
1	C	C

As stated in Clause A2.0 of the BCA, compliance with the National Construction Code is achieved by satisfying (i) the Governing Requirements of the NCC; and (ii) the Performance Requirements.

The BCA provides a set of prescriptive DtS Provisions. The DtS Provisions are defined within the BCA as building solutions deemed to comply with the Performance Requirements of the BCA. Deviations from the DtS Provisions are an acceptable option to comply with the BCA if the Performance Requirements of the BCA are met. The alternative method to demonstrate compliance is called a 'Performance Solution' (formerly known as an 'Alternative Solution').

The Performance Requirements can be satisfied by using one of the following methods, including (i) A performance solution; (ii) a Deem-to-Satisfy (DtS) solution; and (iii) a combination of performance solution and DtS solution, as shown in Figure 8.

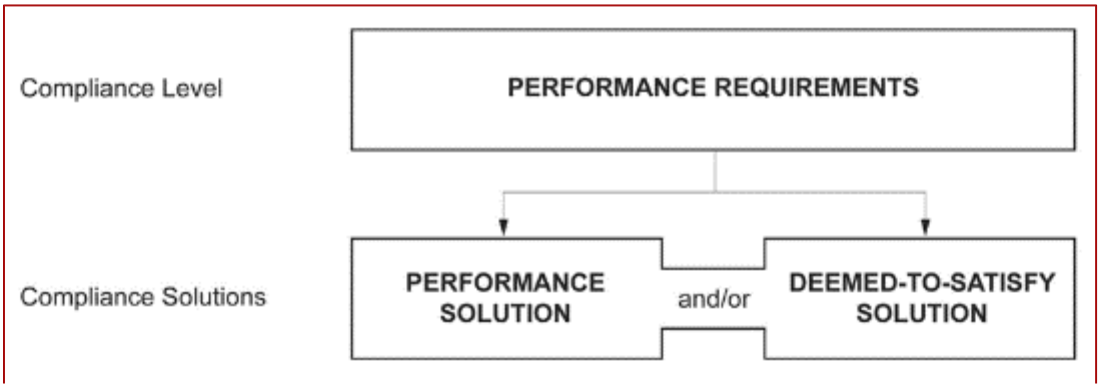

Figure 8: Structure of NCC compliance (ABCB, 2019)

The assessment of a Performance Solution can be undertaken using a variety of methods. These are defined in Clause A2.2(2) of the BCA. One or more, or a combination of these methods can be adopted to determine whether the Performance Solution complies with the Performance Requirements of the BCA. The relevant Performance Requirements have been determined in accordance with Clause A2.2(3) of the BCA. Compliance with Performance Requirements is to be in accordance with Clause A2.1 of the BCA.

When integrating combustible materials such as PV in external walls of buildings of Types A and B construction, the following Deemed-to-Satisfy Provisions in the BCA: Clauses C1.9(a)(i), C1.14(a), C2.6, C2.12, and clause C2.4 of Specification C1.1, are relevant and must be considered. In addition to these clauses, the Verification Method CV3 (Fire spread via external walls) must be considered.

Clause C1.9(a)(i) of the BCA states that, in a building required to be of Type A or B construction, the external walls and common walls, including all components incorporated in them including façade covering, framing and insulation must be non-combustible materials (ABCB, 2019). Thus, the BIPV panels cannot be part of the external wall of Types A and B buildings, because these panels are combustible unless the relevant Performance Requirements CP2 and CP4 are met.

However, the BIPV panels may be attached to the façade of buildings by using non-combustible fixings. When these panels are attached to the external walls or curtain wall façade, the following Building Code of Australia (BCA) 2019 Amendment 1 requirements with respect to fire safety are required to be considered:

(a) Clause C1.14(a) of the BCA states that an ancillary element must not be fixed, installed or attached to the internal parts or externals face of an external wall that is required to be non-combustible unless it is a non-combustible ancillary element or certain exempt materials that are considered low risk (ABCB, 2019). As BIPV is made from combustible materials, they cannot be used as an ancillary element directly attached to an external wall unless the relevant Performance Requirements CP2 and CP4 are met.

(b) If the external wall, to which the BIPV panels are attached, are considered to be exposed to a fire source feature (e.g., the wall is close to the lot title boundary or close to the far side of the road), then the external wall will need to attain a fire resistance level (*Tables 3 and 4 in BCA Specification C1.1 for Types A and B construction respectively*).

(c) In turn, it is required to demonstrate that the use of BIPV to the external wall does not reduce the fire-resistance of the external wall to below that required (*Clause 2.4 of Specification C1.1*).

(d) In buildings of Type A construction, where spandrel panels are required to be provided as a part of the external wall to minimise external vertical fire spread between floors (*Clause C2.6 of the BCA*), the use of BIPV as part of the external wall will need to be demonstrated that it does not increase the risk of external vertical fire spread between floors. There is no specific Deemed-to-Satisfy (DtS) Provision for mitigation of this risk but is captured in the Performance Requirement CP2 that is related to fire spread in buildings and between buildings.

(e) It should also be noted that the BIPV products would need to achieve an FRL level if they are used as part of external walls to comply with Clause C2.6. As the BIPV products are made of combustible materials, this requirement may not be satisfied. However, this problem could be solved by providing sprinkler protection, which leads to C2.6 being satisfied without vertical spandrels achieving an FRL.

(f) The BPIV panels may be considered by the regulatory authority to be a battery system. Clause C2.12 of the BCA requires a battery system installed in the building that has a total voltage of 12 volts or more and a storage capacity of 200 kWh or more must be separated from the remainder of the building by an element having a fire-resistance level of at least 120/120/120.

Since BIPV façades are new to Australia, specific Deemed-to-Satisfy Provisions are not available at present. Thus, the Performance Requirements CP2 and CP4 are relevant:

(a) The Performance Requirement CP2 states that–

- A building must have elements which will, to the degree necessary, avoid the spread of fire to exits, sole-occupancies, public corridors and between building;
- Avoidance of the spread of fire must be appropriate to the function or use of the building; the fire load; the potential fire intensity; the fire hazard; the number of storeys in the building; its proximity to other property; any active fire safety systems installed in the building; the size of any fire compartment; fire brigade intervention; other elements they support; and the evacuation time.

(b) The Performance Requirement CP4 requires safe condition for evacuation. To maintain tenable conditions during occupant evacuation, a material and an assembly must, to the degree necessary, resist the spread of fire and limit the generation of smoke and heat, and any toxic gases likely to be produced, appropriate to the evacuation time; the number, mobility and other characteristics of occupants; the function or use of the building; and an active fire safety systems installed in the building.

In order to achieve Performance Requirements CP2 and CP4, experimental studies must be conducted for BIPV to collect sufficient data on the performance of BIPV in fire condition such as fire resistance level, smoke and heat generation, emitted toxic gases and fire spread.

As stated in Clause A2.2 of the BCA 2019, a Performance Solution must be shown to comply with the relevant Performance Requirements through one or a combination of the following Assessment Methods:

(a) Evidence of suitability that shows the use of a material, product, plumbing and drainage product, form of construction or design meets the relevant *Performance Requirements (Clause 0).*

(b) A verification method, including the following:

- The Verification Methods provided in the NCC.
- Other Verification Methods, accepted by the appropriate authority that show compliance with the relevant Performance Requirements.

(c) Expert Judgement.

(d) Comparison with the Deem-to-Satisfy Provisions.

A Verification Method may include—

(a) A calculation, using analytical methods or mathematical models; or

(b) A test, using a technical procedure, either on-site or in a laboratory, to directly measure the extent to which the Performance Requirements have been met; or

(c) An inspection (and inspection report); or

(d) Any other acceptable form of certification.

In addition to the discussed BCA Clauses, the following relevant Australian Standards should be considered when applying BIPV to buildings:

(a) Design and installation of the solar PV system shall be in accordance with AS/NZS 5033:2014, incorporating Amendment 1 and 2.

(b) The solar PV system and associated equipment shall be labelled with the appropriate labels and signage prescribed by AS 5033:2014, incorporating Amendment 1 and Amendment 2.

In addition to complying with the National Construction Code, the application of BIPV must also comply with other local state and territory requirements. For example, in Victoria, the following guidance documents from Energy Safe Victoria shall also be considered by a suitably qualified electrical engineer [5] in the review of the Solar PV system design and installation:

[5] Suitably qualified electrical engineer means registered building practitioner (RBP) by the Victorian Building Authority in the category of Engineer - Electrical.

(a) New inverter requirements [6]

(b) Installation requirements – Installation and Inspection of Grid-Connected PV systems [7]

(c) Requirements for Solar Alterations [8].

4. Recommended tests for applying BIPV to buildings

The following fire tests need to be considered for application of BIPV in buildings in Australia:

(a) Fire resistance

(b) Reaction to fire (ignitability)

(c) Horizontal and vertical fire propagation

(d) Critical heat fluxes, heat release rate and smoke production

Fire-resistance and combustibility tests

In IEC 61730-2:2018, Clause 10.17 explains the purpose of Fire test MST 23. As the PV module may be exposed to external fire sources, it should be tested for its fire-resistance characteristics when exposed to a fire source originating from outside the PV module.

The fire-resistance test for PV module should comply with local or national building codes, which are developed to specify safety requirements for the application of PV in buildings (BSI, 2018).

The IEC 61730-2:2018 also suggests several international fire tests that can be referred to, including:

(a) ISO 834-1, Fire-resistance tests – Elements of building construction – Part 1: General requirements

(b) ISO 834-3, Fire-resistance tests – Elements of building construction – Part 3 – Commentary on the test method and test data application

(c) ISO 13501-5:2005, Fire classification of construction products and building elements – Part 5: Classification using data from external fire exposure to roofs tests

In Australia, the following standards should be considered for the fire tests, including:

6 https://www.esv.vic.gov.au/wp-content/uploads/2016/12/A3-B1-C1-D9-SafetyAlert_Inverter_Reqs_Oct2016.pdf

7 https://www.esv.vic.gov.au/wp-content/uploads/2016/12/A3-B1-C1-D17-Solar_Installations_Requirements_Sept2015.pdf

8 https://www.esv.vic.gov.au/wp-content/uploads/2016/12/A3-B1-C1-D16-Solar_Instal_PV_alter_Requirements_Aug20.pdf

(a) AS 1530.1-1994 (Reconfirmed 2016), Methods for fire tests on building materials, components and structures – Part 1: Combustibility test for materials

(b) AS 1530.4:2014, Methods for fire tests on building materials, components and structures – Part 4: Fire resistance tests for elements of construction.

Ignitability test

In the IEC 61730-2:2018 standard, the purpose of test MST 24 as discussed in Clause 10.18.1 of the IEC Standard is to determine the ignitability of PV modules by direct small flame impingement under zero impressed irradiance by external heat sources using vertically oriented test specimens (BSI, 2018).

It should be noted that the MST 24 test does not replace a fire resistance test of PV modules or BIPV. This test can only be used to assess ignitability, not flammability of outer surfaces of a module. The details of this test are based on ISO 11925-2:2020: Reaction to fire tests – Ignitability of products subjected to direct impingement of flame – Part 2: Single-flame source.

To conduct the ignitability test, the ISO 5657 Reaction to fire tests – Ignitability of building products using a radiant heat source could be used as a reference.

Horizontal and vertical flame spread

The British Standards BS 8414-1:2020 and BS 8414-2:2020 can be used to determine the performance of BIPV as an external cladding system supported by masonry substrate and structural steel frame in fire conditions, respectively. Figure 9 shows an external cladding fire test setup used in BS 8414-1:2020 and BS 8414-2:2020.

These two standards aim to provide a test method for determining the fire performance characteristics of non-loadbearing external cladding system when fixed to, and supported by a masonry substrate or a steel structural frame and exposed to an external fire under controlled conditions.

The tests suggested in these two standards are to indicate fire spread across or within an external cladding system. The purpose of the tests is to provide data to enable evaluation of the fire performance of the components when combined to form a complete cladding system.

In addition to BS 8414-1 and 8414-2:2020, the reaction to fire tests for façade ISO 13785-1:2002 and ISO 13785-2:2002 can be used to determine fire performance of materials and constructions of façade and cladding. The tests developed in these standards will impose the heat from a simulated external fire with flames directly upon a façade.

In Australia, the fire propagation testing in the standard of AS 5113:2016 can be used to classify external walls of buildings according to their tendency to limit the spread of fire via the external wall and between adjacent buildings. AS 5113 refers to BS 8414-1, BS 8414-2 and ISO 13785-2 as acceptable test standards. It should be noted that the PV panels are typically not active with live electricity condition when they are tested. Therefore, the extrapolation of test results must be carefully considered when applied to live panel in reality.

Apart from the vertical flame spread test, the lateral flame spread test needs to be determined. Examples of lateral flame spread can be seen in Figure 10. This experimental study is based on ASTM-E-1321-13 by establishing an exposing sample to a known incident heat flux.

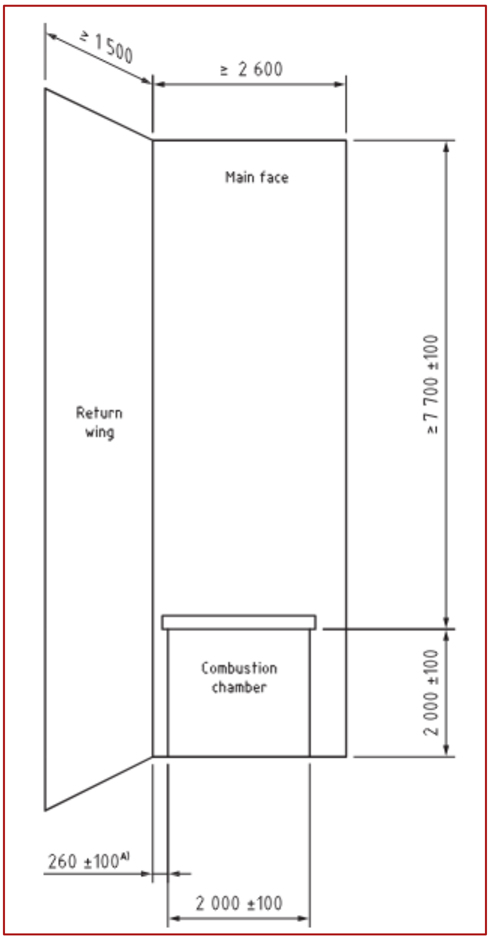

Figure 9: Vertical frame spread test setup (BS 8414-1:2020, BS 8414-2:2020)

Figure 10: Lateral flame spread test (Mazziotti et al., 2016)

Critical heat fluxes, heat release rate and smoke production

It is necessary to determine the critical heat fluxes for piloted and non-piloted ignition, heat release rate and smoke production of PV modules and BIPV.

These critical values can be determined using a cone calorimeter tested according to ISO 5660-1:2015+A1:2019: Reaction-to-fire tests – Heat release, smoke production and mass loss rate – Part 1: Heat release rate (cone calorimeter method) and smoke production rate (dynamic measurement). Examples of cone calorimeter test can be seen in Figure 11.

The heat release rate, smoke production and toxic species yield of each panel assembly may be determined by using the ISO 9705-1:2016 Full-scale room test.

Finally, a thermogravimetric analysis (TGA) can be conducted to determine the thermal decomposition products.

Figure 11: Burning of photovoltaic samples using the cone calorimeter test (Chow et al., 2017)

Fire safety requirements for roof

Effects of fire on the roof:

PV and BIPV roof can be exposed to various fires depending on the source of fire, including internal fires from inside of the building; fires from the BIPV and PV panels; and fires from adjacent buildings.

(a) With a fire starting on the inside of a building, if the PV or BIPV panels or roof tiles are placed on good heat conductors such as light metal roof shells, the temperature of the PV or BIPV could be increased rapidly. If the temperature reaches the ignition temperature (or critical heat flux), the PV or BIPV product could be ignited. As the PV and BIPV products are combustible, the fire on top of the roof could travel and spread until the fuel is completely burnt out or extinguished.

(b) In terms of a fire originating from the PV or BIPV itself, fire can be ignited because of many reasons as summarised in Section 1. Fire can be then spread quickly depending on the physical construction of the roof.

(c) In case of a fire in adjacent buildings: a fire on PV or BIPV products can start because of the radiant heat or flying embers. In this case, the critical heat flux of PV and BIPV must be experimentally determined to evaluate the fire ignition mechanism.

The spread of roof fires:

When a fire occurs on PV and BIPV panels on the roof, the fire can spread through the rooftop and can also be accelerated by wind conditions. When ignited, the burning PV or BIPV products can drip on to the surface or another combustible PV or BIPV below, thus causing a secondary fire. A fire development of this type of construction components could make the extinguishing attempt more difficult or even impossible. The flame could spread and expand on the roof of the building while the building has been extinguishing. Subsequently, the flame can re-ignite the building fire.

BCA requirements for roof tiles

The Australian Standards AS 2049-2002:R2015 only sets out requirements for concrete, terracotta, and other composite roof tiles and for the associated accessories. It does require the material admixtures for roof tiles must comply with AS 1478 and AS 1379, while does not provide any clarification for combustible roof tiles such as PV or BIPV product.

According to the Specification C1.1 of the BCA, the FRL of roof for Type A construction must satisfy the requirements as shown in Table 2. However, the roof is not required to comply with the mentioned requirements in Table 2 if the roofs covering is *non-combustible* and the building:

(a) has a sprinkler system complying with Specification E1.5 of BCA installed throughout; or

(b) has a rise in storeys of 3 or less; or

(c) is of Class 2 or 3; or

(d) has an effective height of not more than 25 m and the ceiling immediately below the roof has a resistance to the incipient spread of fire to the roof space of not less than 60 minutes.

As stated in Clause C1.9 of the BCA, the roof is not a building element that is required to be non-combustible.

Table 2: Type A construction: FRL of roofs

Building element	Class of building – FRL: (in minutes) Structural adequacy/integrity/insulation			
Building class	2, 3, or 4 part	5, 7a or 9	6	7b or 8
Roofs	90/60/30	120/60/30	180/60/30	240/90/60

Risk assessment of BIPV on building's rooftop

When installing PV panels on the rooftop of buildings, the critical hazards associated with the identified risk are:

(a) Fire starting in isolators, inverters, electrical wiring, junction boxes [9] and switchboards, then spreading vertically and horizontally via the PV panels due to their combustible nature.

(b) Electrical shock, failure and degradation of PV components to occupants and firefighters in the event of a fire.

(c) Ignition of adjacent building components due to flame spread, burning droplets, or radiation from the PV panel in the event of a fire.

(d) The risk of fire brigade operations being compromised.

Observed burning behaviour of photovoltaic panels in literature

To understand the behaviour of PV and BIPV panels in fire conditions, several experimental studies have been carried at different levels (Yang et al., 2015; Ju et al., 2018; J. Steemann Kristensen & G. Jomass, 2018). A thorough investigation of the fire behaviour of flexible photovoltaic panels (FPV) installed in BIPV systems is needed before relevant regulations can be formulated (Ju et al., 2018). In this report, the main findings from these experimental studies are summarised and used for initial performance solutions of application PV and BIPV in buildings.

The flammability and fire hazards of PV were conducted using cone calorimeter (Yang et al., 2015). This study focused on understanding several parameters including ignition time, heat release rate, carbon monoxide and carbon dioxide concentration of PV panel in fire conditions.

This study found that multiple fire burnings occurred on the surface of the PV sample after the PV sample was melt and vapour was produced because of high temperature. The vapour was ignited, and flames appeared at different places. These single flames were then merged into a single bigger flame with a cluster of bubbles appearing, indicating that the combustion is *intensive*.

Notably, the cover glass of PV broke into pieces which may cause injuries for firefighter while fighting for PV fires.

Also, dripping behaviour of PV panels was observed during this test, thus raising a concern of fire propagation and spread as well as the safety of firefighters and occupants.

9 https://news.dualsun.com/installation-maintenance/solar-panel-fire/

Yang's study found that the ignition time of PV reduced from 913 s to 83 s when the incident heat flux increased from 28 to 45 kW/m^2, and the critical heat flux, which ignited the PV panels, is 26 kW/m^2 (Yang et al., 2015). This critical heat flux level is greater than those found in Ju's study (Ju et al., 2018) in which the critical heat flux of flexible PV is 20 kW/m^2. These range of incident heat fluxes are quite common in residential fires or compartment fires (Welch et al., 2007). Thus, the PV panel is likely catching fire by flame heat flux.

In addition to the fire behaviour test of PV module, Yang's study found that PV panel is a thermally thick material, which formed a temperature gradient (i.e., non-linear temperature distribution) within the sample cross-section of PV module (Yang et al., 2015). Because of this non-uniform distribution of temperature, the PV module tends to bow towards the heating source (i.e., incident heat flux or flame) due to the non-uniform thermal expansion, thus leading to the breakage of the protective glass. This finding is entirely consistent with the experimental observation, where the protective glass of PV breaks into pieces as highlighted above.

Yang's study also focused on the heat release rate (HRR) of the PV/BIPV panel because it represents the rate of thermal energy generated by the PV/BIPV module by combustion. This parameter is the key to fire growth rate as well as the smoke and gaseous generated by PV/BIPV in a fire condition. If the HRR is large enough, it can ignite the adjacent combustible components, leading to the fire propagation (Yang et al., 2015). Based on the HRR, the total heat release (THR) of a material can be calculated, indicating the fire hazards of the material.

By increasing the incident heat flux from 28 to 45 kW/m^2, Yang found that the peak HRR of PV module increase from 85 to 402 kW/m^2, and the THR of PV module ranges from 38.3 to 50.1 MJ/m^2.

Flame spread underneath the PV panel arrays on the flat roof was investigated by using experimental study (J. Steemann Kristensen & G. Jomass, 2018). It is found that the main cause for fire spread within PV arrays is the re-radiation caused by PV panels in a fire. Also, the construction and installation of PV panels play a significant role in fire propagation. Therefore, the fire-related risk of PV panels and BIPV also depends on materials of the existing roof and other combustible components. This study concluded that the initial fire underneath of PV panel arrays can transform into a hazardous fire scenarios scenario due to the changing fire dynamics associated adding the PV panels to the existing roof, and recommended that proper management should be taken to mitigate the fire risk of PV panels.

A study conducted by Ju on flexible PV (FPV) found that the critical heat flux is 20 kW/m^2 which is smaller than those are found in Yang's study (Ju et al., 2018; Yang et al., 2015). The ignition temperature of FPV was estimated at 693 K (420 °C), which is close to the measured value in the experimental study. Besides, the peak heat release rate increases from 390 to 705 kW/m^2 as the heat flux increases from 20 to 70 kW/m^2.

Summary of required tests and evaluation

Table 3 summaries the proposed tests that can be conducted to collect data for Performance Solution:

Table 3: Fire tests for BIPV

Test No.	Test categories	International standards	Relevant Australian Standards	Engineers' Evaluation	Requirements for Fire Performance Solution
1	Fire-resistance test	IEC 61730-2:2018 ISO 834-1 ISO 834-3	AS 1530.1-1994 (Reconfirmed 2016) AS 1530.4:2014	A fire should not spread from the PV, BIPV into the building via the combustible materials.	Information from these tests can be used in determining if or how a BIPV could be used close to an allotment boundary where the wall or spandrels are required to be fire-resistant. Occupants should be able to evacuate with adequate measures for egress, warning signs and electrical safety before the onset of untenable conditions. Firefighters should be provided with adequate measures and safety to perform fire brigade operations.

Test No.	Test categories	International standards	Relevant Australian Standards	Engineers' Evaluation	Requirements for Fire Performance Solution
2	Reaction-to-fire test (Ignitability)	IEC 61730-2:2018 ISO 11925-2:2020 ISO 5657 EN ISO 11925-2 [10]	N/A	- Ignite temperature - Critical heat flux - Ignition time	Information from these tests can be used to assess the risk of ignition of the PV/BIPV, impacting if it can be used for example on the ground floor or close to balconies where ignition sources are more common.

10 This test evaluates the ignitability of a product under exposure to a small flame.

Test No.	Test categories	International standards	Relevant Australian Standards	Engineers' Evaluation	Requirements for Fire Performance Solution
3	Vertical and lateral fire propagation Burning behaviour	BS 8414-1:2020 and BS 8414-2:2020 ISO 13785-1:2002 and ISO 13785-2:2002 EN ISO 9239-1 [11]	AS 5113:2016 [12]	- Flame spread behaviour vertically and horizontally	Information from these tests can be used to assess the risk of undue fire-spread between windows or balconies via the PV/BIPV, impacting the location of where the PV/BIPV can be used. Similarly, information regarding dripping behaviour can be used to assess the risk of fire-spread via falling burning drops or pieces from the PV/BIPV, impacting where and how the PV/BIPV can be used.

[11] This test evaluates the critical heat flux below which flames no longer spread over a horizontal surface.
[12] This Standard sets out the procedures for the fire propagation testing and classification of external walls of buildings according to their tendency to limite the spread of fire via external wall and between adjacent buildings. This test does not distinguish the live condition of PV panels when they are tested.

Test No.	Test categories	International standards	Relevant Australian Standards	Engineers' Evaluation	Requirements for Fire Performance Solution
4	Critical heat fluxes, heat release rate and smoke production	ISO 5660-1:2015+A1:2019 EN ISO 1716 [13]	N/A	- Critical heat flux - Heat release rate - Total heat release - Smoke and gas compositions	Information from these tests can be used when assessing the risk of smoke-and fire spread from the panels, for example, if BIPV/PV is proposed at locations where fire or smoke is at risk of impacting egress routes.
5	Single burning item test	EN 13823 [14]	N/A	- This test evaluates the potential contribution of a product to the development of a fire, under a fire situation simulating a single burning item in a room corner near to that product.	Information from this test can be used to assess the probability and consequences in the initial face of a fire, for instance, if BIPV/PV is close to a possible ignition source. This could impact where and how the BIPV can be used.

[13] This test determines the potential maximum total heat release of a product when completely burning, regardless of its end use (BS EN 13501-1-2007).

[14] This test evaluates the potential contribution of a product to the development of a fire, under a fire situation simulating a single burning item in a room corner near to that product.

Test No.	Test categories	International standards	Relevant Australian Standards	Engineers' Evaluation	Requirements for Fire Performance Solution
6	Full-scale room test	ISO 9705-1:2016 [15]	N/A	This standard specifies the test method to evaluate the reaction of wall and ceiling products to fire when installed at the surface of a small room and exposed directly to a specified ignition source. The test represents a fire scenario, which starts under well-ventilated conditions in the corner of a specified room with a single open doorway.	Information from this test can be used to assess the probability and consequences in the initial face of a fire, for instance, if BIPV/PV is close to a possible ignition source. This could impact where and how the BIPV can be used.

Performance Solution discussion

To do a Performance Solution to allow for BIPV use in a building, a fire safety engineer would use the data from available tests to discuss the risks associated with the BIPV in relation to the relevant Performance Requirements of the BCA. Moreover, the location and configuration of the BIPV in relation to the use and design of the building would need to be assessed. Among other things, a Performance Solution is likely to consider:

(a) The location of the BIPV in relation to possible ignition sources. For example, BIPV on walls facing balcony could be ignited by a barbecue.

[15] This standard specifies the test method to evaluate the reaction of wall and ceiling products to fire when installed at the surface of a small room and exposed directly to a specified ignition source. The test represents a fire scenario, which starts under well-ventilated conditions in a corner of a specified room with a single open doorway.

(b) The location of the BIPV in relation to openings in the façade or roof. For example, a fire between two windows aligned vertically could spread from one to the other via the BIPV.

(c) The location of the BIPV is in relation to exits from the building. For example, dripping burning droplets from a BIPV over an exit could compromise safe egress of the occupants and make fire brigade intervention more difficult.

(d) The wall construction behind the combustible parts of the BIPV. For example, a fire inside a building could spread to the BIPV through the wall and spread further via the façade.

(e) The fire safety measures, such as sprinkler and detection and alarm system, are installed in the building. For example, sprinkler reduces the likelihood of severe fires in the building and detection and alarm systems impacts the time for occupants to evacuate the building.

(f) The possibility for firefighters to safely access and attack a fire involving BIPV.

Given the considerations mentioned above, depending on how a particular BIPV product perform in the standardised tests outlined in this report, the BIPV may be more likely to be of use on specific parts of the building. More specifically, it can be harder to show through a Performance Solution that BIPV can be used:

(a) Close to adjacent buildings.

(b) Between vertically aligned openings.

(c) Where dripping or falling BIPV can start a secondary fire below.

(d) Close to or over exits from the building.

(e) In buildings where a sprinkler system is not installed.

5. Conclusions

Fire safety is a vital concern for the application of BIPV to buildings in Australia. It is essential to ensure that the application of BIPV will not adversely affect the fire and life safety of occupants and the structural performance of buildings.

Currently, the Building Code of Australia does not have Deemed-to-Satisfy Provision for installation of BIPV on the façade and the roof of most buildings. The relevant Performance Requirements are CP2 and CP4.

Although the application of PV on the rooftop has been widely adopted within Australia, the application of PV as external walls for the building is new and requires to be carefully considered to ensure the safety of occupants and buildings.

To reduce the fire risk of BIPV to occupants and buildings, the following aspects must be fully considered.

(a) When BIPV is applied in building Types A and B (typically multi-residential buildings or other buildings with more than two storeys), the following Deem-to-Satisfy Provisions in the BCA must be considered including C1.9(a)(i), C1.14(a), C2.6, C2.12, and C2.4 Specification C1.1.

(b) Tests must be conducted to collect sufficient data of BIPV performance at high temperature, including (i) fire resistance test; (ii) reaction-to-fire test (ignitability); (iii) vertical and lateral fire propagation; and (iv) critical heat fluxes, heat release rate and smoke production.

In addition to the mentioned clauses and tests, the application of BIPV to buildings must comply with Performance Requirements or satisfy other relevant Australian Standards listed in Sections 3 and 4 as well as the requirements of local states and territories in Australia. It should be noted that Performance Solution can be done using sufficient data to satisfy Performance Requirements.

Several Australian Standards can be used to evaluate the performance of BIPV at high temperature, including (i) AS 1530.4:2014; and (ii) AS 5113:2016. The installation and safety requirements for PV arrays listed in the Australian Standard AS/NZS 5033:2014 Amendment No. 1 and 2 must also be met.

Other than that, to satisfy the requirements for fire safety when BIPV is used as part of façades, the international standards listed in Section 4 should be considered.

A Performance Solution is likely to address a large number of provisions to accurately show the BIPV complies with the Performance Requirements. This includes the properties of the BIPV, the location of the BIPV, the building construction, use of the building and type of occupants, egress routes, fire safety provisions such as sprinkler and alarm systems and fire fighting provisions.

BIPV can likely be used only on limited areas on a building, depending on these provisions and the behaviour of a BIPV in standardised tests. Furthermore, it might be that larger areas of BIPV can be used on non-residential buildings where occupants are not sleeping.

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