Large- and small-scale fire test of a building integrated photovoltaic (BIPV) façade system

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ARTICLE INFO

Keywords:
Facade
BIPV
Full-scale fire test
Reaction to fire
Cavity
Cone calorimeter

ABSTRACT

The number of installed photovoltaic (PV) modules has increased significantly over the last years, and using available building surfaces to generate electricity by integrating PV modules in the construction is an attractive option. Building integrated photovoltaics (BIPV) or other vented claddings can spread fires rapidly to large parts of a building if the fire is allowed to propagate. To investigate this hazard, a large-scale SP FIRE 105 façade fire test was conducted. A façade measuring 4000 mm × 6000 mm covered with BIPV modules was exposed to flames that represent the fire plume from a window in a room at flashover. The results from the test show that critical failures, like falling objects and vertical flame propagation, can be expected in such constructions. These results highlight the importance of details in mounting of BIPV-facades and to require proper documentation from relevant fire tests of such systems. Small-scale cone calorimeter tests were conducted on the studied BIPV module to provide material properties of the combustible parts of the installation. These aspects should be considered when planning new or when retrofitting façades, to prevent escalation of fires. The results presented are, however, only valid for the configuration that was tested. Other BIPV-facades should also be investigated to study how these constructions can be built safely in the future with regard to critical details.

1. Introduction

With an increasing focus on environmental sustainability and reducing carbon footprints, installing photovoltaic (PV) modules on building envelopes (i.e., roofs, façades, windows) has gained a growing interest, with many new and innovative products over the last years [1]. The increasing energy cost and the decreasing cost of PV installations have further enhanced this trend [2]. Depending on the building location, orientation, light conditions and geometry, the façade can be an attractive surface for installation of PV systems. At high latitudes, the angle of the sun is lower than closer to the equator, and vertical façades can receive more sunlight. The solar mutual reflections from buildings and from ground covered by snow can further increase the irradiance on vertical façades, making this option particularly interesting in such locations [3]. However, vertical façades may also pose fire safety challenges. Fires spreading in façades can reach large parts of a building in a short time, and several large fires have occurred in high-rise buildings over the past decades, including the dramatic Grenfell Tower fire in London (UK) in 2017 [4]. Bonner and Rein have found an increasing trend in the number of such fires, pointing to the increasing complexity of design and technology in modern façades and the increasing use of different combustible materials to meet requirements connected to thermal insulation and aesthetic appearance [5]. The International Energy Agency (IEA) defines building integrated photovoltaic (BIPV) modules as PV modules that are designed to be a construction product, and that would need to be replaced by another construction product if dismounted, as opposed to building attached photovoltaics (BAPV) that do not fulfil any construction purpose [6]. BIPV modules in façades share many of the same construction details as other modern façade systems, including ventilated cavities and combustible polymer materials. Unlike passive façade systems with cladding panels, PV modules include electric connections that represent potential ignition sources inside the ventilated cavity. Other aspects, like the routing of PV cables and optimization of electric output, further increase the complexity of BIPV façade systems. Current codes and standards for electrical products and for building products do not address all the fire safety issues that may occur in BIPV façades [7]. Understanding the fire behaviour of a BIPV façade at full scale is not possible from the small scale reaction to fire tests that are listed in IEC 61730-1 and –2 [8,9], where the back of the PV module is exposed to a

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https://doi.org/10.1016/j.firesaf.2023.104083
Received 14 July 2023; Received in revised form 8 December 2023; Accepted 20 December 2023
Available online 25 December 2023
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small flame to assess ignitability based on the test EN ISO 11925 [10]. A survey of 218 PV products was conducted by Yang et al. and showed that most of the products only listed compliance with IEC 61730, which does not require any large-scale fire test [11]. Large-scale façade tests, like AS 5113, BS 8414, ISO 13785 and NFPA 285 are required by the regulations in some cases in the UK, Switzerland, Canada, USA and Australia for the use of combustible materials on external walls [11]. However, there is limited data for BIPV systems tested according to such large-scale tests, at least in the publicly available literature.

This study aims to illustrate how a complete assembly of BIPV modules, fixing system, sealing details and wall construction can perform in a façade fire. Although only one single large-scale experiment was performed with one BIPV-façade system, the tested system includes materials and constructions that are commonly used in PV systems. The fire dynamics and failure modes of the tested façade construction are described to illustrate how such façades can cause fire hazards despite complying to all relevant safety standards. Additional small-scale tests of the BIPV modules in the cone calorimeter are presented to quantify how easily the modules ignite and how much heat is released from the combustible materials in a fire. This data is also used to compare the current BIPV façade to other PV modules and to other types of modern ventilated façade materials.

2. Material and methods

The BIPV system used in the current study is commercially available and consists of custom-sized modules with a glass front and a polymer back. The frame and fixing system are made from aluminium. Further details on the modules are given in Section 2.1, and the façade system in Section 2.2 below.

The full-scale façade experiment was conducted according to SP FIRE 105 [12], which is a large-scale façade test method referenced in the building regulations in Sweden, Norway, and Denmark. One of the undamaged BIPV modules from the façade test was later dismantled and cut into smaller pieces, measuring 100 × 100 mm² and tested in the cone calorimeter according to ISO 5660-1 [13] to provide reaction to fire properties of the combustible materials in the modules.

2.1. BIPV modules

The tested BIPV modules are listed to comply with IEC EN 61730-1 and -2 [8,9]. These standards include requirements for electrical, mechanical and material properties of the PV module construction, and how these properties shall be tested and documented in 31 different tests. Six of these tests are related to fire hazards, of which one is a reference to national regulations of fire requirements when PV modules are installed on buildings. In four of these tests the temperature is monitored under different operating conditions. Finally, the only required test that includes flame exposure is an ignitability test based on the small-flame test ISO 11925-2 [10]. A match-sized flame is impinging different surfaces of the module for 15 s and no flame spread beyond 150 mm is allowed for 20 s.

The modules are also complying with the design qualification and type approval of crystalline silicon PV modules, IEC EN 61215, which implies a series of 18 different tests [14]. In one of these tests the module is exposed to 200 thermal cycles in a climatic chamber between −40 °C and +85 °C. Electric current shall flow uninterrupted through the module during the cycles while the temperature is above +25 °C. After the cycles, the module shall not be visually defect, the maximum output power shall not be reduced by more than 5 %, and the module shall have the same insulation resistance as before the test.

The front face of the module was classified as Euroclass B,s1,d0 according to EN 13501-1 [15], which means that it had been tested with a small flame according to ISO 11925 [10] and in the Single Burning Item test (SBI) according to EN 13823 [16].

The modules had a glass front and an unspecified polymer backsheet. The aluminium frame was glued to the backsheet giving a frameless design, except for a small lip of the frame that supported the top and bottom edges of the glass. A plastic junction box made from polyphenylene ether and polystyrene (PPE + PS) measuring 116 mm × 110 mm × 22 mm with connecting leads and connectors was glued to the back of each module near one of the short edges. The back of one of the smallest modules can be seen in Fig. 1.

The mass of the modules ranged from 14.1 kg to 5.6 kg including junction box and connecting cables. Most of this mass was glass and aluminium, but approximately 12 % was made from different plastic materials. The main parts of the module were separated and weighed, and the mass fraction of the different parts for the largest and smallest module size were calculated and are presented in Table 1. As the same type of junction box, cables and connectors were installed on all modules, these represent a higher mass fraction on the smaller modules due to the lower module mass. The polymers laminated to the glass are evenly distributed across the module area and represent a lower fraction of the mass in the smaller modules. Still, the total fraction of polymers is 12 % for both the smallest and largest module.

The thickness of the different layers of the PV module was measured with calipers and is presented in Table 2. Some uncertainty on the individual layer thicknesses should be assumed as the layers were not easy to separate for the measurements.

2.2. BIPV façade system

The tested construction consisted of a façade BIPV system installed on a timber frame wall with combustible wood fibre insulation covered with gypsum boards. The BIPV installation was made with rectangular PV modules mounted on aluminium rails on the gypsum boards. The modules were from 603 to 735 mm wide and from 560 to 1460 mm high. A total of 26 modules were custom-made to cover the façade measuring 4000 mm × 6000 mm (W × H), excluding the two window openings measuring 1510 mm × 1200 mm (W × H). The layout of the modules on the façade test rig is shown in Fig. 2 (a). Each module in the façade is labelled and addressed from A1 to E6 for later reference. A side view of the façade system through the lower window opening is shown in Fig. 2 (b).

The aluminium fixing system supported each row of modules on two horizontal rails attached to the wall. The distances between the modules were 20 mm horizontally and 40 mm vertically. The vertical gaps between the modules were sealed with an aluminium profile, and the horizontal gaps were open. The railing system allowed a free flow of air
behind the PV modules with a cavity depth of approximately 65 mm but with a narrower passage of approximately 23 mm, where the horizontal members on the top and bottom of the PV module frame blocked parts of the cross section. This air cavity was sealed at two locations with intumescent cavity barriers across the full width of the façade above the lower edge of the façade and above the lower window, as seen in Fig. 2 (a). When used against wood or gypsum boards, these cavity barriers have fire resistance between EI30 and EI90 in different configurations, which means that the barrier can prevent temperature increase and flames on the unexposed side for 30 and 90 min when exposed to a standardized time-temperature fire curve.

The cavity was open in the vertical edges of the façade and around the window openings except for the top of the lower window, where the cavity barrier was installed.

The connectors of the modules were not interconnected during the experiment, and the cables for each module were coiled inside the aluminium frame on the module as seen in Fig. 1. The test was conducted indoors in low ambient light. Any voltage generated by the solar cells would be isolated within each module.

2.3. Large-scale façade test

The Nordic SP FIRE 105 test method is one of several different large-scale façade tests that are used to assess complete façade systems exposed to flames from a compartment at flashover [17]. The heat source in the test is a pool fire with 60 L of heptane located in the fire room below the façade, as seen below the dark BIPV modules in Fig. 2 (a). The façade includes two fictitious windows that shall not be covered by the façade system, but where the details of the façade system shall be installed as it would in practice. In calibration tests with non-combustible façades, the heat flux in the lower window shall be above 15 kW/m² for at least 7 min, and above 35 kW/m² for at least 1.5 min. This heat flux measurement in the lower window and additional plate thermocouples facing the façade at different heights at 3 m distance were also installed in both the calibration tests and the BIPV façade test. These measurements allow comparison of the heat exposure

<table>
<thead>
<tr>
<th>Layer</th>
<th>Measured thickness</th>
</tr>
</thead>
<tbody>
<tr>
<td>Glass</td>
<td>3.2 mm</td>
</tr>
<tr>
<td>Encapsulant *</td>
<td>0.4 mm</td>
</tr>
<tr>
<td>Silicon solar cell</td>
<td>0.2 mm</td>
</tr>
<tr>
<td>Encapsulant *</td>
<td>0.4 mm</td>
</tr>
<tr>
<td>Backsheet *</td>
<td>0.3 mm</td>
</tr>
<tr>
<td>Sum</td>
<td>4.5 mm</td>
</tr>
<tr>
<td>Sum polymers *</td>
<td>1.1 mm</td>
</tr>
</tbody>
</table>

Table 1

Dimensions and mass for the largest and smallest modules used in the façade test and mass fractions of the main plastic parts for each module.

<table>
<thead>
<tr>
<th></th>
<th>Largest modules</th>
<th>Smallest modules</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dimensions W × H</td>
<td>735 mm × 1460 mm</td>
<td>603 mm × 560 mm</td>
</tr>
<tr>
<td>Total mass</td>
<td>14.10 kg</td>
<td>5.61 kg</td>
</tr>
<tr>
<td>Polymers laminated to the glass</td>
<td>10.5 %</td>
<td>8.2 %</td>
</tr>
<tr>
<td>Polymers in junction box</td>
<td>0.8 %</td>
<td>2.1 %</td>
</tr>
<tr>
<td>Cable insulation</td>
<td>0.5 %</td>
<td>1.4 %</td>
</tr>
<tr>
<td>Cable connector</td>
<td>0.2 %</td>
<td>0.4 %</td>
</tr>
<tr>
<td>Sum polymers</td>
<td>12.0 %</td>
<td>12.1 %</td>
</tr>
</tbody>
</table>

Fig. 2. Test configuration with BIPV-system installed on the SP FIRE 105 large-scale façade test rig. (a) The BIPV façade seen from the front with each module labelled from A1 to E6. Locations of temperature measurements are shown in red with indications of Left (L), Center (C) or Right (R) and the distance in mm from the lower edge of the BIPV-façade. The cavity barriers span across the façade and can be seen where they extend out on the left side. (b) The frame and fixing system of the BIPV façade as seen where the BIPV modules meet the lower window opening. The cavity barrier can also be seen behind the module frame above the window. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)
to the façade and to the neighbouring building from the heptane fire in the calibration test, and any additional heat generated by the combustible façade materials.

The guidance for the Norwegian fire regulations accepts results from tests according to SP FIRE 105 or similar methods as documentation for fire behaviour of combustible façade insulation systems [18]. In our case, combustible insulation was used inside the wood frame wall, and was covered with gypsum boards.

In addition to the temperature measurements required by the SP FIRE 105 test method, temperatures were measured with type K thermocouple wires with twisted ends in the locations shown in Fig. 2(a). The temperatures were measured on the outside surface of the BIPV modules (PVS), in the centre of the air cavity between the modules and the gypsum board (AC), and on the surface of the gypsum board (GS). The measurement points were spread out across the façade to get an overview of the temperature distribution during the experiment. Each point is a local measurement, and the absolute value may have been different in other locations or in repeated tests with varying fire propagation and flow patterns.

As the experiment was conducted as a qualifying test for the façade construction, the additional instrumentation could not interfere with the performance or integrity of the construction.

2.4. Cone calorimeter tests

To provide detailed reaction to fire properties of the combustible materials in the BIPV modules, a series of cone calorimeter tests were conducted according to ISO 5660-1 [13]. This apparatus can measure a wide range of parameters, of which the critical heat flux, heat release and mass loss were the most relevant to understand how the modules contributed to the fire propagation in the façade. The critical heat flux is calculated from the time to ignition at different heat flux levels, the heat release is calculated from the oxygen depletion measured in the smoke according to ISO 5660-1 and the mass loss from a scale below the test specimen holder.

Test specimens were made from one of the undamaged BIPV modules after the façade test. The module was cleaned for soot deposits, and the aluminium frame and junction box were removed from the module by cutting the glue with a thin knife along the back of the glass. The glass front with solar cells, encapsulant and backsheet was cut into squares measuring 100 mm × 100 mm using a water-cooled diamond saw. As the glass was cut, it shattered into small fragments. The structural rigidity of the glass pane was noticeably reduced, but the glass fragments were held in place by the remaining layers. The test specimens were conditioned at 23 °C and 50 % relative humidity until a stable mass was achieved before the tests.

The polymer backsheet of the test specimens was exposed to heat fluxes in the range of 20–50 kW/m² in the horizontal orientation. Each test was repeated 2 to 3 times. The glass face and sides of the test specimens were covered with aluminium foil and supported on non-combustible insulation material in the specimen holder. A spark igniter was located 13 mm from the centre of the specimen surface.

Additional tests were also done with the test specimen and cone heater in the vertical orientation with heat fluxes between 20 and 65 kW/m². The glass side of the specimens was supported with a wireframe and fixed with a steel sheet jammed between the side walls of the specimen holder, as seen in Fig. 3. This allowed the glass surface to be exposed to the ambient air through the open back of the test specimen holder. The igniter was placed at the same location as in the horizontal tests, relative to the test specimen. This location is not according to the specified location in ISO 5660-1 annex E [13], which states that the igniter shall be placed 5 mm above the top of the specimen holder where the concentration of the pyrolysis gases are assumed to be highest. The position used can allow more of the pyrolysis gases to be released unignited as they rise along the surface of the specimen up and away from the igniter. This could also be the case in a vertically propagating façade fire where the heat from the fire would come from below and allow some of the pyrolysis gases to be released upwards unignited.

The junction box plastic represented the second highest fraction of combustible mass on the modules and the plastic lid of the junction box was tested in the horizontal orientation at an incident heat flux of 50 kW/m².

3. Results and discussion

The results from the façade test, based on observations from video recordings and temperature measurements, and the results from the cone calorimeter tests are presented and discussed in this section. Results from each test scale are discussed individually, and finally it is discussed how the results from the small-scale tests relate to the observed fire development and propagation in the large-scale test.

3.1. Fire development

The façade test lasted for a total of 30 min from ignition until the heptane in the fire room had burnt out. After that, the façade was still burning, and the test was continued until the fire had propagated to the top of the façade and eventually self-extinguished after 47 min. The façade fire test can be divided into three different stages based on the characteristics of the fire. The transitions between these stages are somewhat gradual and are driven by the development of the fire from the ignition of the heptane pool in the fire room to the fire propagating up to the top of the façade. An outline of the different stages is included in Table 3 and illustrations of the fire during the different stages can be seen in Fig. 4.

The first stage of the fire lasted for approximately 15 min, while the fire room was heated up towards the flashover. During this stage, there were no flames emerging from the fire room, but the hot gases from the fire heated the surface of module A3 at 750 mm height to 300 °C and the air in the cavity behind the module to 150 °C as seen in Fig. 5(b) and (d). All the other thermocouples measured temperatures between 30 °C and 76 °C after 15 min. Initially, the temperatures in the façade were around 15 °C. Fig. 5 shows all the measured temperatures in the façade during

<table>
<thead>
<tr>
<th>Stage</th>
<th>Duration</th>
<th>Dominated by</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0–15 min</td>
<td>The fire room is heated up towards flashover.</td>
</tr>
<tr>
<td>2</td>
<td>15–30 min</td>
<td>Large flames from the fire room expose the façade.</td>
</tr>
<tr>
<td>3</td>
<td>30–47 min</td>
<td>Self-sustained propagating fire in the façade.</td>
</tr>
</tbody>
</table>
the test. Fig. 4 (a) shows the time when the flames start to emerge from the fire room and expose the lower part of the façade.

The modules shall be tested with thermal cycling up to 85 °C according to IEC EN 61215 [14]. The operating temperature in a BIPV façade depends on the ambient and ventilation conditions, and will in many cases vary around 50 °C [19–21]. This means that most of the BIPV façade was at temperatures more representative for an operative façade after 15 min than it was when the test started.

The second stage of the fire lasted from 15 to 30 min and was dominated by large flames and large amounts of black smoke that emerged from the fire room. Fig. 4 (b) shows the flames at their peak intensity 25 min into the test. The smoke covered most of the façade during this stage making detailed observations challenging. The temperatures in the cavity behind row A of BIPV modules (L 750 AC, C 750 AC and R 750 AC) reached more than 800 °C, as seen in Fig. 5 (c), (d) and (e), and large parts of the aluminium fixing system of the two lower rows of modules melted. All the modules in the two lower rows, A and B, fell down during this period as shown in Fig. 7. Burning parts and debris fell to the ground below the façade from this point and continued burning throughout the test, as seen in Fig. 4 (b), (c) and (d).

From the high temperatures measured in the two lower rows of modules during the intense flames from the heptane in the fire room, it is no surprise that the construction made with glass, aluminium, glue, and polymers suffered severe damage. This does not compare to the minor heat exposure a module is exposed to in the small-flame test required to comply with EN IEC 61730 [8,9].

During the third stage, the fire in the façade was propagating self-sustained upwards in the cavity on the left side of the window, as seen in Fig. 4 (c) and (d). From the lower edge of row C to the top of the façade, the flame propagated in approximately 8 min, from 27 to 35 min into the test. With a vertical distance of 3.2 m, the average flame spread rate could be estimated to 0.4 m/min during this period. Modules C5 and C6 on the right side of the windows were also exposed to the flames from the modules below, but after modules B5 and B6 fell down, the fire on this side of the façade self-extinguished.

The propagating fire can also be tracked by the cavity temperature measurements on the left side as seen in Fig. 5(c), where the temperature in the cavity on the left side increases first behind module A2 at L 750 AC after 21 min, then behind module C2 at L 3200 AC and L 3700 AC after 27 min, and finally behind module E2 at L 5700 AC after 34 min 2–3 min after the temperatures increased, the modules at each location fell down.

Echoes of these distinct temperature increases caused by the propagating fire can also be seen in the measurements from the centre and the right-hand temperature rise in the façade as seen in Fig. 5(d)–(f) indicating that hot gases are diverted sideways across the façade from the fire propagating on the left side of the windows. The same temperatures are shown in Fig. 6(a) and (b) for the cavity temperatures at row C and E respectively. The horizontal transfer of hot gases did not cause horizontal fire propagation despite these high recorded temperatures.

The heat flux measured in the lower window, and the temperatures on the plate thermocouples facing the façade were in fact slightly lower in the test with the BIPV façade, than in the calibration test with a non-combustible façade. This implies that the added combustible material in the BIPV installation did not increase the heat flux into the window opening, or towards any potential neighbouring building.
3.2. Falling parts

The glass panes of twelve of the modules loosened in large pieces and fell to the ground. An overview of the time for the different modules can be seen in Fig. 7. In most of these modules, the glass pane loosened from the aluminium frame and fixing system that remained on the façade throughout the test. In addition to these modules, parts of the glass on modules D1, D2 and E1 fell down, even though this was not registered as a collapse and included in Fig. 7.

The mass of each falling part was not measured, but the biggest glass panes weighed almost 10 kg. This would represent a great hazard for firefighters or other people below the façade. It can be questioned if a more temperature resistant adhesive, or a metal frame supporting all edges of the glass pane could prevent the large panes from falling out in large pieces. More secure and temperature resistant fixing of the glass panes could possibly prevent the large panes from falling down in one piece, but probably not prevent them from shattering and falling down in smaller pieces. The latter would however represent a far lower hazard than the large falling panes that were observed in the test.

As the glass panes fell down, the combustible material was removed from the façade, and the flames stopped exposing the modules above. This was clearly observed in module B6, where the flame exposure onto modules B5 and B6 had fallen down. Parts and debris from the façade kept burning on the ground throughout the test, as seen in Fig. 4 (b), (c) and (d). This may cause the fire to spread to other surfaces below the façade.

3.3. Cavity barrier and fire spread

The cavity barrier installed across the entire width of the façade at the lower edge of rows A and C was inspected after the test. The intumescent material was expanded and appeared to have sealed the gap against the aluminium lower part of the module frames. The barrier along the lower edge of the façade was, however, completely bypassed.
On row C, the aluminium frame that the barrier was sealed against was mostly intact, but the glass in module C1 was damaged, and the glass on module C2 had fallen off, creating a bypass into the cavity above the barrier. It is not known exactly how the fire propagated past the barrier or at what time the glass was damaged, but the cavity temperatures above the barrier increased rapidly after 27 min from 135 °C to around 500 °C. 30 s later, flames were observed from the cavity, and the temperature increased further to 800 °C.

On the right side of the window, at modules C5 and C6, the flames were also impinging on the cavity barrier without propagating past the barrier or penetrating the module glass. The sudden temperature increase in the cavity here coincides with the ignition behind module C2 as mentioned above. Despite this high temperature, no fire damage was observed in the cavity above the barrier on this side during the examination after the fire.

These different outcomes of the fire barrier performance illustrate the complexity of how the different components interact and work together in a fire. The flames from the modules below impinge on the higher modules and the cavity barrier. The wall construction and any exposed combustible material could also contribute to the fire spread. How all these materials and assemblies interact cannot be replicated in any small-scale test in a realistic way. Studying the reaction to fire of such complex systems can hence only be done in large-scale tests with a complete construction assembly. A deeper understanding of how these materials behave in large-scale can still be a foundation to determine critical parameters that can be tested in a smaller scale and reduce the probability of severe fire propagation in real façades.

3.4. Cone calorimeter

The calculated heat release rates (HRR), accumulated total heat release (THR) and mass loss (ML) are shown for one typical test at each different incident heat flux rate for the vertical and horizontal orientation in Fig. 8. The HRR reached a peak shortly after ignition and started declining after this. The peak was higher and occurred earlier for the higher incident heat flux levels than for the lower levels. In the horizontal orientation, the HRR tended to level out at a plateau during the decline as seen in Fig. 8(b). The mass loss followed the heat release and is shown in Fig. 8 (e) and (f). For the vertical tests, the mass loss data is shown to the time when pieces started falling off and the measurements became unstable. The mass loss of tests at 20, 25 and 30 kW/m² incident heat flux in the vertical orientation is also included in Fig. 8 (c) while the heat release is not included as these test specimens did not ignite.

The burning behaviour of the vertically installed specimens was assessed as the most representative for the end use application for façades and increased the complexity of these tests. When the rear surface was exposed to the radiant heat, the plastic backsheet and encapsulant started to melt, flow and emit smoke. Some of the plastic material started dripping from the test specimen and down onto the heat shield below. Observations were made through the glass side on the unexposed side of the test specimens, where flowing plastic and silicon fragments could be clearly seen. Some of this material flowed into the bottom of the
test specimen holder and some of it dripped from the test specimen. The glass was shattered into smaller fragments from cutting the module into test specimens, and these fragments were initially held in place by the intact laminated layers. As these laminated layers melted and burned off, the glass fragments were only supported by the metal grid in the specimen holder and eventually fell out from the specimen holder during the test. These different modes of mass loss in addition to the mass loss from combustion made the recorded mass of the test specimen difficult to use for further analysis.

The loss of flowing plastic may explain the lower total heat release for the vertical tests as seen in Fig. 8 (c) and (d) for heat exposure respectively 50 kW/m² and 33 kW/m². The larger difference at the lower heat flux level may be caused by the longer time to ignition, where more of the combustible material had time to flow away from the test specimen surface. The additional delay in ignition caused by the location of the igniter in the vertical tests may have further increased this difference. Some reduction in heat release may also be caused by pyrolysis gases being released without igniting due to the low position of the igniter. Although all these effects of mass loss from the test specimen are relevant for the façade installation, the total heat release from the materials in the BIPV modules is represented better by the results from the horizontal test, where the molten plastic and glass fragments remained in place throughout the tests.

Ju et al. [22] tested a similar type of PV module in the cone calorimeter with the back face exposed to 25–45 kW/m². The modules used by Ju et al. had the same five-layer construction as the ones used in the current study, and quite similar thickness of combustible layers, but a thinner glass. The peak heat release rate, time from test start to the peak heat release and total heat release are plotted in Fig. 9 (a)–(c) for the current tests together with data from Ju et al. The results from Ju et al. show slightly higher peak heat release rates and shorter times to ignition but lower total heat release than the tests in the current study.

The critical heat flux for ignition is calculated according to the method proposed by Janssens [23], where the time to ignition to the power of −0.547 plotted against the incident heat flux should fall in a straight line for thermally thick materials, as shown in Fig. 10.
The critical heat fluxes were calculated to be 3.8 and 20.2 kW/m² for the current tests plotted with the results from tests presented by Ju et al. [22].

The critical heat flux for ignition is calculated as the intersection with a linear best-fit curve through these points and the x-axis to be 3.8 and 20.2 kW/m² for the current tests and data from Ju et al. [22], respectively. The critical heat flux for the vertical tests is not calculated, as the igniter was not located in the location with the highest concentration of pyrolysis gases and may have delayed the ignition, particularly for the lower heat flux levels.

The critical heat flux calculated to 3.8 kW/m² is very low and would in theory imply that the material would ignite in an infinite time when exposed to this heat flux. However, as commented by Babrauskas [24] on page 260, there exists a maximum time of ignition when the combustible products are exhausted and no ignition is possible after this point. An overview of calculated critical heat fluxes and minimum heat flux where ignition is achieved is also provided by Babrauskas [24] in Table S7 on page 265 where materials like wood particleboard (WP), polyurethane (PU) and polymethylmethacrylate (PMMA) are listed with critical heat fluxes in the range 3.08–4.7 kW/m², and minimum heat fluxes in the range 8–13 kW/m². This effect was clearly observed in the vertical tests with incident heat flux below 33 kW/m² where the specimens did not ignite during a 50-min exposure, and the smoke production and mass loss peaked and decreased before 5 min into the test. The concentration of flammable pyrolysis gases would also peak and decrease during this time, and if no ignition was achieved during this period, it would not be possible to ignite at any later time under the same heat exposure.

The steeper curve through the data from Ju et al. [22] corresponds to a lower thermal inertia according to Janssens theory [23]. This is in line with the thinner glass in the modules used by Ju et al. (2.3 mm) compared to the glass used in the current study (3.2 mm). Other differences between the module types can be caused by different amounts of flame retardants added to the polymers. The higher and earlier peak heat release rates from the modules used by Ju et al. should imply that the fire would propagate faster in the façade compared to the modules used in the current study. On the other hand, the higher critical heat flux calculated for the modules used by Ju et al. means that they can resist more heating without igniting. With the high heat exposure from the full-scale façade fire test, or the fully developed cavity fire, this is not likely to make any difference, but in the case of a smaller ignition source caused by an electrical fault or another minor heat source, this higher critical heat flux could prevent the fire from spreading to the modules. This illustrates that the heat release of the ignition source in combination with the reaction to fire properties of the surrounding materials can be important parameters when assessing whether a fire will develop and propagate or not.

The plastic in the junction box lid ignited after approximately 60 s when exposed to 50 kW/m², which is 15 s faster than the BIPV modules under the same conditions. The mass of the combustible materials in the box was lower than the mass of combustible materials laminated to the glass as seen in Table 1. The results from the box materials are normalized to the module area and compared to the results from the glass specimens tested under the same conditions. The total heat release from the junction box material was 8 % and 26 % of the heat released from the glass test specimens per unit area of the largest and smallest modules respectively. This is also in line with the difference in total mass of combustible materials in the junction box and in the glass laminate for the largest and smallest modules, as the average effective heats of combustion were almost identical, being 30.5 MJ/kg for the glass laminate and 31.0 MJ/kg for the junction box material.

Assuming the same effective heat of combustion also for the small amounts of plastics in the cable insulation and connectors, the total heat of combustion per unit area of the modules were 48 MJ/m² and 62 MJ/m² for the largest and smallest modules respectively. For the total 26 modules of different sizes used in the large-scale façade fire test, this makes an average of 53 MJ/m² across the façade.

### 3.5. Bench-scale to large-scale

Fire safety of building products are to a large extent based on small- or medium-scale reaction to fire tests as the ones used for classification according to EN 13501-1 [15]. In general, these test methods have their limitations in their small sizes and the limited ability to include a
complete system as built in its end use application. For façade constructions, a range of large-scale test methods have been developed to be able to include a representative end use application for complete façades. Two examples are the BS 8414-1 [25] that is used in the UK, and the SP Fire 105 [12] that is used in the Scandinavian countries.

McKenna et al. [26] investigated different modern façade cladding and insulation materials in the cone calorimeter. A total of 11 different façade cladding materials, like aluminium composite material (ACM), high pressure laminate (HPL) and mineral wool board (MWB) and insulation materials made from phenolic foam (PF), polyisocyanurate (PIR), stone wool (SW) and glass wool (GW) were tested. Two different models were suggested for predicting the result of façades tested with combinations of these materials in the large-scale BS 8414-1 façade fire test [25] based on a series of tests performed after the Grenfell fire [27].

In the first model suggested by McKenna et al. [26] the total heat release from the façade cladding and insulation material tested in the cone calorimeter at 50 kW/m$^2$ incident heat flux were added. 68 MJ/m$^2$ was suggested as the maximum total heat release from the materials to predict a passed large-scale test according to the BS 8414-1 [25]. The BIPV modules had a total heat release of 53 MJ/m$^2$ which is lower than 7 of the 11 cladding panels in McKenna’s study, and well within the suggested threshold. But with the addition of one of the combustible PF or PIR insulation materials, the threshold could be passed.

The second model suggested by McKenna et al. [26] was to sum the peak heat release rate of the cladding and the insulation. A threshold of 157 kW/m$^2$ was suggested to pass the large-scale façade test. The BIPV modules in our study released a peak heat release rate of 359 kW/m$^2$, meaning that they would be predicted to fail the large-scale test without any additional contribution from any combustible insulation. In fact, only 3 of the 11 façade cladding materials tested by McKenna et al. released higher peak heat release rates than the BIPV module.

The BS 8414-1 test method is not identical to the SP Fire 105, but they are both large-scale façade fire tests, where preventing fires from spreading in the ventilated cavities is crucial to pass the test. As the large-scale test also challenges the structural integrity of the façade components, including cavity barriers, it can be argued that a simple model based on only total heat release, or peak heat release rate is insufficient to predict the fire behaviour of a complete façade. However, particularly for the cavity and outer surface fire propagation, the peak heat release rate will be an important parameter to predict the fire spread. This parameter was also emphasized by Babrauskas and Peacock [28] as the single most important reaction to fire parameter to cause fire hazards in room fires, as it is the speed of released heat that drives the heat transfer that escalates the fire. In a cavity fire, the heat is concentrated up into the cavity above the fire, as compared to a room fire where the heat from a burning object is diluted and spread across the area of the room. This means that the peak heat release rate is of particular interest for assessing the cavity fire propagation, and that the BIPV modules pose a relatively high risk compared to many other modern façade cladding materials.

The limited amount of combustible materials in the BIPV modules, and the passed module-scale tests described in IEC 61730 [8,9] and the ones referenced in EN 13501-1 [15] were not sufficient to prevent a propagating fire in a façade covered with these modules. Despite the relatively low total heat release from the combustible materials in the BIPV modules, the peak heat release rate is quite high and can contribute to a rapid fire propagation in a cavity fire as seen in the large-scale façade tests. In case the surface inside the cavity of the BIPV modules would contain more combustible materials than the gypsum boards used in the current experiment, the heat released from this material would also contribute to the fire propagation. This could be combustible insulation like polyisocyanurate (PIR) or phenolic foams (PF) as studied by McKenna et al. [26], a combustible wind barrier cloth or other types of combustible materials.

Fire propagation in the horizontal cavity under PV modules installed on flat roofs has been studied in bench-scale by Kristensen et al. [29,30]. In these studies, the contribution from the combustible material on the PV modules were considered to be negligible, and similar results were obtained with non-combustible stainless-steel plates as with actual PV modules with combustible backsheets. This experiment shows that even the limited amount of combustible material on the back of the BIPV modules was sufficient to cause a self-sustained vertically propagating fire in the cavity. It should be noted that the experiments by Kristensen et al. were performed with 2 mm polymethyl methacrylate (PMMA) [29] and a gas burner [30] representing the fuel load from the building surface where the additional combustible material from the PV modules was found to give an insignificant contribution. The horizontal orientation configuration in Kristensen’s work also gave different flame characteristics and lower flame spread rates compared to the vertical orientation in the present study.

4. Summary and conclusions

In this study, a BIPV façade measuring 4000 mm × 6000 mm with 26 PV modules was tested according to the large-scale façade test method SP FIRE 105. The glass-polymer BIPV modules were mounted with a ventilated cavity on gypsum boards. The fire development during the test was divided into three stages. Firstly, preheating the fire room and façade before the flashover. Secondly, large heptane flames exposed the two lower rows of modules. Finally, flame propagation in the cavity from the third row to the top of the façade. It was found that the large heptane fire from the fire room below the façade caused severe damage to the two lowest rows of modules causing all these modules to fall down in a short period of time. The highest measured temperatures reached 850 °C in the cavity during this stage. After the heptane fire had burnt out, the fire was able to propagate self-sustained past the cavity barrier and to the top of the façade causing additional modules to fall down. The observations from this test illustrate several challenges to preventing fire propagation in BIPV façades. The main findings can be summarized in the following points.

- Vertical flame propagation in the cavity is possible with very limited amounts of combustible material.
- The integrity of the glass, glue and aluminium construction was compromised by the high temperatures in this large-scale fire.
- Sealing the cavity with fire barriers can be challenging if the fire resistance of the surrounding components is compromised.
- Small-flame ignitability tests currently used to qualify BIPV modules give very little information relevant for the fire development in a BIPV façade.
- Small-scale reaction to fire tests can give useful results on the material properties related to ignition and heat release of the materials in the construction.

The fire safety engineer should evaluate if these issues are relevant for any project with a BIPV façade. If a fire performance with vertically propagating flames and falling debris is not acceptable, an assessment should be made whether these situations can happen with the relevant construction. Relevant documentation and, if possible, large-scale fire tests of the façade system, as it will be used in the project, should be requested.

Further research can investigate how BIPV façades can be built and what details and parameters are crucial to avoid fire spread and falling parts. If such parameters are identified and sufficiently understood for full-scale BIPV installations, different materials and products can be tested and verified in small-scale tests and installed in real buildings without compromising the fire safety.

CRediT authorship contribution statement

Reidar Stølen: Conceptualization, Data curation, Formal analysis, Funding acquisition, Methodology, Project administration, Writing –
original draft, Writing – review & editing. Tian Li: Conceptualization, Data curation, Formal analysis, Funding acquisition, Investigation, Methodology, Project administration, Resources, Software, Supervision, Visualization, Writing – review & editing. Trond Wingdahl: Data curation, Formal analysis, Investigation, Project administration, Resources, Writing – review & editing. Anne Steen-Hansen: Conceptualization, Formal analysis, Funding acquisition, Methodology, Supervision, Writing – review & editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

Acknowledgements

This research is supported by the Fire Research and Innovation Centre (FRIC), funded by the Research Council of Norway (Project no. 294649) and project partners. The authors would also thank the C40 Centre (FRIC), funded by the Research Council of Norway (Project no. 113112).

Data will be made available on request.

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