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Review

Fire safety of building integrated photovoltaic systems—State of the art

Michaela Zamrazilova

Faculty of Military Leadership, University of Defence, 66210 Brno, The Czech Republic; michaela.zamrazilova@unob.cz

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Abstract: The main long-term goal of international communities is to achieve sustainable development. This issue is currently highly topical in most European Union (EU) countries due to the ongoing energy crisis. Building Integrated Photovoltaics (BIPV), which can be integrated into the building surface (roof or facade), thereby replacing conventional building materials, contributes significantly to achieving zero net energy buildings. However, fire safety is important when using BIPV as a structural system in buildings, and it is essential that the application of BIPV as building facades and roofs does not adversely affect the safety of the buildings, their occupants, or the responding firefighters. As multifunctional products, BIPV modules must meet fire safety requirements in the field of electrical engineering as well as in the construction industry. In terms of building regulations, the fire safety requirements of the BIPV must comply with national building regulations. Within this article, aspects and fire hazards associated with BIPV system installations will be defined, including proposals for installation and material requirements that can help meet fire safety.

Keywords: fire safety; photovoltaic systems; BIPV; sustainable development

1. Introduction

Electrical energy can easily be converted into kinetic energy, heat energy, light energy and transmitted over long distances. Modern human society is increasingly dependent on electricity, and any major outage can lead to damage that can have an impact on the very functioning of the state (Karda and Kavan, 2023; Kavan et al., 2021). In view of this, there is an increasing use of renewable sources to produce electricity. In the case of solar energy, in the first two decades of the current millennium alone, there has been an exponential increase in the global energy capacity produced by photovoltaic (PV) installations from a capacity of 0.54 GW in 2000 to 1185 GW at the end of 2022 (Masson, 2023). PV systems are available in all sizes, from a single PV cell mounted on the wall of a power bank, to domestic and commercial installations on buildings, to ground installations of nearly 1 GW, such as the Longyangxia Dam Solar Park in China (Voiland, 2017). The increased number of photovoltaic systems is associated with a continuous reduction in the cost of photovoltaic modules and thus the cost of energy, which makes them attractive to commercial and family property owners (Kristensen et al., 2022).

The requirements for sustainability in the construction and operation of buildings are defined by the "Europe 2030 Strategy." One of the main objectives of the EU investment strategy is to address climate change by reducing greenhouse gas emissions and fossil fuel consumption, and to provide reliable, sustainable, modern and affordable energy sources for the operation of buildings so that to achieve carbon neutrality by 2050. In line with this strategy and the Renewable Energy Directive (RED), the target is to cover 32% of energy consumption from renewable sources (European Parliament, 2018).

Comparing statistical data from the Institute for energy research shows annual global energy consumption is on an upward trajectory, increasing by approximately 8–10% and projected to increase by 40% by 2040, as shown in **Figure 1**. Primarily, this increase is due to economic development in developed countries, which expect a substantial increase in global energy demand by 2040. Thus, renewable energy can be expected to supply 14% of primary energy by 2040, as shown in **Figure 1**. (IER, 2018).

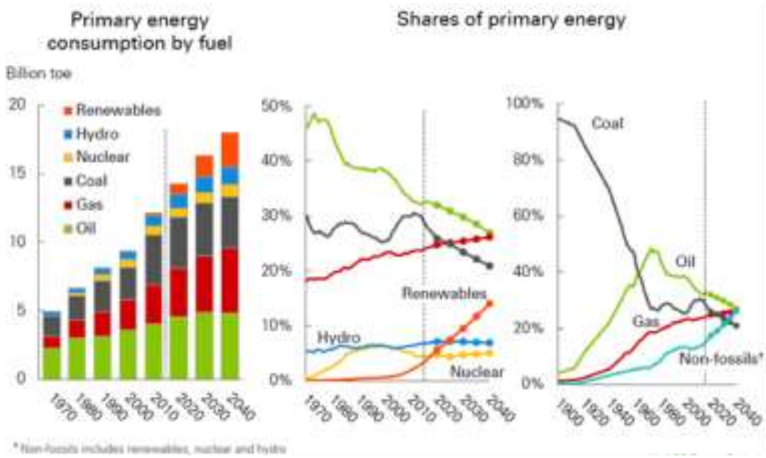

Figure 1. World energy consumption (IER, 2018).

These requirements can only be met by the active use of such technologies in buildings that would obtain energy primarily from renewable sources and then be able to transform it for operational needs. Solar energy is the most available source that can provide energy for optimizing the thermal microclimate and operational technical equipment of buildings during their construction in temperate climate conditions. Solar radiation is the unlimited and most available source of renewable energy. If the potential of its use from the radiating surfaces of buildings with built-in PV modules is increased, there will be significant independence from non-renewable energy sources and a reduction of the environmental burden (Iringova, 2022).

Unlike conventional building-adapted photovoltaic systems (Building Applied Photovoltaics—BAPV), BIPV systems are used as integrated building elements. The electricity-generating modules are both a functional unit of the finished building and a structural element of the building envelope, as they replace conventional materials. This approach defines the BIPV as an architecturally relevant component, as an active energy-producing unit that also adds aesthetic value to the entire structure. This applies to both new buildings and renovations, as many architecturally attractive post-industrial, but also traditional pre-war and post-war apartment buildings are undergoing modernization (Heinstein et al., 2013).

In addition to energy harvesting, integrated PV modules are suitable for contributing to buildings' internal comfort. It serves as weather protection, shading modulation, noise protection, thermal insulation, etc. Since choosing this route replaces entire parts of the building envelope, there are savings in building material costs. PV modules are now able to replace the covering of the entire roof and supply electricity at the same time, this also applies to the elements used in the façade of the building. After the initial expenditure of planning and financing costs, the multifunctionality of BIPV thus has a favorable effect on the total costs of the construction project and on the amortization of the PV system itself (Prume and Viehweg, 2015). However, it should be noted that PV installations cause an increased probability of ignition (Kristensen et al., 2022; Prume and Vieweg, 2015) and the physical presence of PV modules changes the fire dynamics of the existing roof structure (Ju et al., 2019; Kristensen et al., 2018; Kristensen et al., 2020).

For example, the flame spread caused by PV panels on the roof is related to the height of the gap, the slope and the insulation material (Kristensen et al., 2022). Moreover, PV panels have been shown to be flammable structures causing fires in buildings (Iringova, 2022). It is essential to ensure that the use of combustible BIPV on facades or external walls and roofs ensures the fire safety of building occupants, facilitates extinguishing and prevents the spread of fire to neighboring properties. Photovoltaic power plant (PVP) components can affect the spread of fire outside the building, interfere with the ventilation of smoke and other combustion products, impede firefighting operations, and introduce new electrical shock hazards to firefighters (El-Sherrif, 2017).

To mitigate the danger of fire in buildings, fire codes and standards provide guidance on the management of fire prevention measures for minimal loss of life and property damage. Depending on the function of the building, fire codes and standards prescribe appropriate design strategies and assessment approaches (Kodur et al., 2020). Since BIPV is a new technology developed in recent years that has a potential fire hazard, there is yet no clear direction on the standardized fire hazard assessment of BIPV worldwide (Yang et al., 2023).

In general, statistics on PV plant-related fires are sporadic, but an analysis that was published by Mohd Nizam Ong et al. (2022) estimated the annual fire frequency to be 28.9 fires per 1 GW of capacity. A 2013 German survey identified a total of 430 fires related to PV systems (Prume and Viwheg, 2015). In 2019, J.F. Weaver reported in PV Magazine that the number of fires related to PV systems in Arizona alone has gradually increased from 25 in 2015 to 56 in 2018 (Weaver, 2019). Mohd Nizam Ong et al. also found in their analysis that fire safety was often included in the installation instructions covering the electrical part of the technology, while fire safety related to the interaction with the building itself was rarely mentioned in the design (Mohd et al., 2022). With an expected lifetime of PV systems of 25 to 40 years, understanding the long-term fire risk of PV systems is considered essential to ensure sustainable development of the technology (Kristensen et al., 2020).

Based on the above, it is possible to state that there is currently no unified approach to solving fire safety or it is being neglected. Although the standards for photovoltaic systems in various countries directly or indirectly refer to the standards IEC 61215, IEC 61730 and UL 1703, it is not entirely clear how current products meet regional standards for photovoltaic systems and/or building standards, yet enter the local market in a given country, which can result in adoption complexities and knowledge gaps. In order to form an opinion on this issue, this document compares regulations and standards in different countries.

The integration of PV into buildings requires a thorough performance assessment in accordance with building regulations and standards. A review of national and international fire safety requirements that apply to PV installations will allow the PV industry and installation companies to better understand the performance of solar building envelopes under fire conditions and identify related fire tests. The findings will add to our current knowledge and reduce BIPV fire safety hazards and impacts by facilitating the development of design and construction standards.

2. Methodology

A targeted review of the literature was used as part of this work. The selection of literature, accepted theories and concepts was carried out for basic work with a specific focus on the existing problem of BIPV installations. Case studies were used to identify deficiencies associated with fires. Peer-reviewed articles, research reports, reports from the media and online information sources were used for a targeted review of the literature.

From the analysis of the professional literature presented above, the growth of electricity consumption and the demands for their acquisition, it follows that the use of BIPV installations will grow in importance. An important operational and safety issue of BIPV is the solution to fire safety, therefore the research focused on the risks associated with installation in individual building elements. Based on these facts, the aim of this article is to present individual aspects related to fire in the context of installed BIPV systems and to summarize the requirements for ensuring fire safety in terms of installation and material composition.

3. Results and discussion

The trend of converting buildings from energy users to energy producers is not something that has just emerged. In 1986, the Swiss engineer Markus Real was the first to take the initiative and invited 333 homeowners in Zurich to install photovoltaic panels on their roofs, thus giving birth to the idea of using PV for decentralized energy generation. Already in 1990, the first buildings with BIPV installation began to be built worldwide. The public service building in Aachen (Stadtwerke Aachen) can serve as one of the first examples among many others (Heinstein et al., 2013).

Among the first publications related to BIPV was the work published in 1993 by the Swiss authors Humm and Toggweiler (Humm and Toggweiler, 1993). Programmatically, it carried the integration of solar cells into building envelopes in its name, and for a long time represented one of the few sources within Europe. It was there that the first implementations of BIPV were presented, which for reasons dictated by time were mostly limited to the integration of standard modules based on silicon (Si) wafers. In 1997, task 7 of the PV Power System program of the International Energy Agency (IEA) was launched. Its goal was to increase the architectural and technical quality and economic viability of photovoltaic systems. This international cooperation program was conceived to link the development of photovoltaics in Europe, the USA, Japan and Australia (Heinstein et al., 2013). In 2000, a paper on the management of BIPV was published in the USA. Using the example of 16 successfully implemented construction projects from around the world, a number of different possible applications and systems integrated into the building from a technical and aesthetic point of view were described and discussed in detail (Eiffert and Kiss, 2000).

In the Anglo-American sphere, this work served for some time as a compendium for other approaches to the topic and stimulated the implementation of many new

BIPV projects. In Germany, the publication "Solararchitektur für Europa" (Schneider, 1996) brought further initiatives, followed by important works on the architectural processing of solar cells (Rexroth, 2001). All over the world, projects have been successfully implemented that have been featured in a large number of publications and improved technologies and systems have been introduced. Several publications have focused on specific categories of buildings, such as residential buildings and commercial buildings. Research has also been conducted on individual structural elements such as facades and different types of roofs, while others have explicitly investigated the multifunctional aspect of PV systems (Heinstein et al., 2013).

3.1. Installation options

Advancements in photovoltaic technology are paving the way for more cost-effective BIPV. The growing interest in this form of solar panel installation stems from the large volume of existing buildings that could benefit from the easy installation of BIPV. The solar cell glazing design is praised for its potential in solar shading, daylight transmission and increased electricity generation. However, the implementation of BIPV in residential buildings remains less common due to the limited scope of roof retrofits, so BAPV tends to be the more common choice (Biyik et al., 2017; Kumar et al., 2019).

A favorable climate makes PV installations a viable business, although demographic constraints present challenges in making significant advancements in production and market expansion. **Figure 2** shows the market share for BIPV, BAPV and open rack-mounted photovoltaic (ORMPV) in selected European PV markets, namely Italy, Germany, France, and Spain. France in particular led the BIPV market share with around 60%, followed by Italy, Spain and Germany with 30%, 2% and 1% respectively. Finally, the BAPV market was dominated by Germany with an 82% share, followed by Italy, Spain, and France. Finally, Spain led the ORMPV market with a 75% share, followed by Italy, France and Germany (Constantinou et al., 2023).

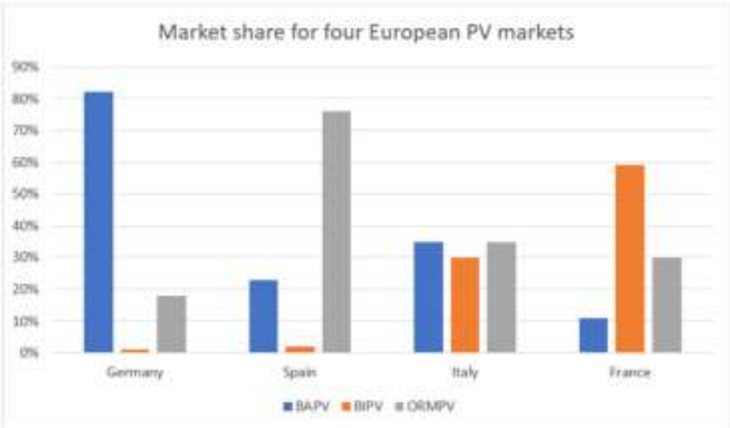

Figure 2. Market share for four European PV markets.

BIPV systems are the optimal solution for new buildings. The PV panels are incorporated into the building envelope and external additional structures. Their effective area is usually larger than that of BAPV systems. They are often used in all-glazed facades oriented to the south, southeast or southwest in urban areas (meant in the northern hemisphere) with a low degree of external shading by surrounding buildings (Iringova, 2022).

They can be built into the shading slats of sunshades, balcony railings, awnings and the like. It is possible to apply them to large skylights and atrium glazed roofs or to replace the classic covering of pitched roofs. If BIPV systems are applied in general renovation of the building envelope, it is possible to achieve the energy efficiency of a building with zero energy consumption (Sorgato et al., 2018; Gholami, 2019).

PV systems can also be implemented as photovoltaic thermal systems with active or passive ventilation behind the panels and subsequent redirection of hot air into the heating system. PV modules are cooled by air or water (Gholami et al., 2015; Mohammadi et al., 2016), so the production of electricity and heat in the building is more efficient (Ihrahmi et al., 2014; Tripathy et al., 2017). For example, a BIPV ventilated in the air gap of a double skin facade or roof typically has the PV system installed in front of the building's inner skin. The backside of the BIPV is naturally ventilated and cooled by fresh summer air, increasing the efficiency of electricity production. If the BIPV uses this extracted hot air for heating, it goes into a new configuration called a building-integrated photovoltaic thermal system. The application of BIPV is not limited to the building; it can also be used in vehicles such as ships, cars or airplanes, contributing to their optimal performance in terms of energy consumption (Iringova, 2022).

3.1.1. Roof systems

Rooftops are so far considered the ideal field for BIPV applications, as sloping roofs with a certain angle provide the best energy utilization. Standard roof systems are among the most common BIPV installations, in which case the PV modules simply replace the roof covering. The well-integrated system is embedded into the surrounding roof tiles with a frameless modular construction. Watertightness must be guaranteed, for example, by means of a specific construction of vertical rails, a horizontal covering of the module and an impermeable intermediate layer underneath. An alternative solution is frame modules. However, architects perceive them as less attractive because the frame is considered as another visible material. In addition to rooftop installations that only cover part of the roof, full roof coverage of PV modules is considered a more economical and elegant alternative (Heinstein et al., 2013).

A new trend is the installation of semi-transparent photovoltaic systems, the advantage of which is the transference of natural daylight into buildings. In addition, their innate ability to modulate the penetration of light and heat increases the quality of the indoor environment and potentially reduces dependence on artificial air conditioning systems. (Stephanos et al., 2023). Roof covering and skylights have been proposed as the most promising integration elements in Australia given the serious fire safety issues of BIPV facades (Wijeratne et al., 2022).

3.1.2. Facades

The second main area of use for BIPV is facades, where solar panels of all technologies can be integrated as a conventional cladding system for exterior walls and single-layer facades. By combining BIPV and thermal insulation, versatile applications emerge that can provide an ideal representation of how BIPV needs to interface with traditional building practice. PV facades require complex planning and compliance with many physical properties. However, many of these requirements are also enabled by multifunctional design (Heinstein et al., 2013).

Within the facade, it is also possible to integrate photovoltaic materials into the glazing. The results of the He et al. (2011) study showed that a window with photovoltaic material based on amorphous silicon can reduce internal radiant heat gains by 46.5% in summer. In addition, this double-glazed window can reduce the temperature of the inner surface of the glass. Wang et al. (2021) found that windows with cadmium-tellurium-based material can improve heat transfer in winter and summer and reduce building energy consumption. Based on the studies mentioned, there is a trade-off between PV windows in terms of PV coverage (energy production capacity), daylight transference and heat gains. Larger solar generation capacity typically results in smaller visible light transference and lower solar thermal gain. At the same time, a more pronounced PV coverage also affects the view of the residents of the interior spaces. It can be stated that for PV cells made of different materials, there are changes in the spectral distribution of solar energy through the PV window (Aste et al., 2018), which needs to be evaluated.

3.2. Fire safety aspects

Since BIPVs meet the requirements of PV modules, the same concern of fire hazard arises because the fire behavior of BIPV modules is influenced by the electrical activities of PV modules (Yang et al., 2023). Photovoltaic systems raise many issues for firefighter safety, such as extinguishing live equipment alone, tripping hazards, and limited walking spaces on roof structures, to name but a few (Namikawa, 2017). Sometimes fires are not initiated by PV panels but start in buildings. It is crucial for the PV industry and fire departments to understand how a PV system affects fire spread and how best to extinguish these fires (Dhere and Shiradkar, 2012).

EU countries use their national guidelines for designers and firefighters. The principles for placing a PV system on the roof are based on the document “Operation of photovoltaics and firefighters: Best practice in selected countries”. Photovoltaic systems, VdS 3145: 2017-11 (02). This regulation is valid in the EU (Namikawa, 2017). The international standards IEC 61215 and IEC 61730 are standards for PV systems used in almost all countries, except for the USA and Canada, where the UL 1703 standard is adopted. If a PV module has been certified according to IEC 61215, this standard represents the module’s quality of use and compliance with electrical requirements. IEC 61215 is intended to apply to all ground modules with flat plates, such as crystalline silicon and thin film modules. IEC 61730 is intended to ensure that PV modules provide electrical and mechanical operational safety throughout their expected lifetime. IEC 61730 specifies basic design requirements for PV modules to ensure safe electrical and mechanical operation. The UL 1703 standard for flat panel photovoltaic modules and panels is also an industry standard for basic safety and performance (Yang et al., 2023).

Current research on PV systems is divided into two groups, the first group considers PV modules as a fire load (Despinasse and Kruger, 2015; Yang et al., 2015), the second group does not (Ju et al., 2019; Kristensen et al., 2018; Kristensen et al., 2020), therefore it is necessary to understand whether, for example, PV panels affect flame propagation.

Fire hazard

Fire hazards can occur at all stages such as installation, operation, maintenance including repair and replacement. It should also be noted that a burning BIPV product can affect the fire resistance and fire response of other building elements around it. Due to the flammability of BIPV modules, potential fire hazards of BIPV systems can be identified as ignition due to hot spots, arcing or faulty installation. Furthermore, it concerns the spread of fire, risks for people in the building and for firefighters during an intervention (Yang et al., 2023).

Ignition is considered the primary BIPV fire hazard that can occur during the installation, operation, and maintenance process (Aram et al., 2021). The ignition of the PV panel itself has the impact of damaging the entire BIPV module, which means that it is likely to lead to the fire of other parts of the BIPV modules (Mazziotti et al., 2016). From another point of view, BIPV modules can also catch fire when exposed to a building fire, and a PV panel could catch fire due to radiant heat if the total heat received exceeds the critical heat flux (Kristensen et al., 2018). PV modules can be ignited when heat fluxes are higher than 26 kW/m^2 (Yang et al., 2015). The potential fire hazard of ignition is likely to result from defects in the BIPV modules and electrical faults. Hot spots, arcs, and short circuits due to poor connection are the main reasons for ignition of BIPV modules (Despinasse and Kruger, 2015).

Photovoltaic cells have been found to experience hot spots due to various defects, including partial shading, material defects, manufacturing errors, and degradation over time (Yang et al., 2023). For these reasons, partial shading is a specific fault condition that causes localized hot spots. When a cell or group of cells is reverse biased, it dissipates energy rather than transmitting it, resulting in excessively high temperatures. The resulting short-circuit current is lower than that of other cells in the series chain, which results in an abnormal increase in temperature on the surface of the damaged cell and the formation of a hot spot (Dhmish et al., 2018).

Sparking can be considered as another typical cause of ignition (Guan et al., 2019). The reason for this phenomenon may be due to malfunctions or incorrect installation. Improper installation of modules can generate enough thermal energy to trigger an arcing short circuit, which can then cause a fire (Chen et al., 2019). In addition, a poor connection that is not tight and has low resistance is one of the main reasons for overheating, which probably triggers the high temperature of electrical components (Yang et al., 2023).

It takes less than 0.1 s to ignite the polymer back layer and the polymer materials in the region adjacent to the diode and junction box (Bower et al., 2012). In addition, the accumulation of impurities (e.g., oxide) on electrical contacts can cause resistive heating, resulting in breakdown of materials and subsequent arcing (Gholami et al., 2015).

Another potential hazard of BIPV is the spread of fire because BIPV modules contain flammable materials (Yin et al., 2018). Polyethylene-co-vinyl acetate (EVA) and polyvinyl butyral (PVB) are the main materials used as BIPV encapsulants. Both EVA and PVB are flammable. According to Glass for Europe (Glass for Europe, 2015), the calorific value of PVB and EVA is 30 MJ/kg and 40 MJ/kg. The spread of fire and smoke from BIPV modules can affect the fire safety of the whole building (Aram et al., 2021) because BIPV modules can facilitate the rapid spread of fire from the ignition point to other parts of the building. According to recent research, both the type of installation and the location of BIPV modules affect the spread of fire. Fire can spread in four ways, up through the facade (e.g. cavities, chimney effect) or by other paths, down through the facade or burning debris, to other floors and to neighboring buildings, typically by radiation (Yang et al., 2023).

Compared to roof mounting, BIPV modules installed on vertical facades are considered to be a greater fire hazard (Ju et al., 2017). According to the results of burning tests of PV panels, the behavior of BIPV is determined by the back sides of the panels (Despinasse and Kruger, 2015).

There is a high probability of ignition of a BIPV panel when exposed to a heat flux above 35 kW/m^2. In addition, if there is a vertical cavity between the BIPV modules and other external wall components, the modules can spread flames and smoke to the upper parts of the facade through this cavity and subsequently to other parts of the building, such as interior spaces and roofs (Yang et al., 2023). When a fire breaks out on PV or BIPV panels installed on a roof, the spread of fire along the roof can be accelerated in windy conditions. When ignited, the burning PV product may drip onto the roof surface or onto another flammable PV panel below and cause a secondary fire (Kristensen et al., 2020). PV systems are able to produce energy with a voltage in the range of 600 to 1500 V. Even at low current, this high range of DC voltage is dangerous for firefighters (Nair, 2018).

Also, batteries cannot be neglected. Although they are not a mandatory part of the system for BIPV projects, they still represent a critical issue as a fire hazard (Kim et al., 2019).

Three factors may be relevant in relation to the safety of people in the building, namely the impact on evacuation, falling parts of PV panels and toxic gas emissions. In relation to firefighter safety, the main potential fire hazard during firefighting operations is electrical shock (Yang et al., 2015).

4. Discussion

Hot spots, arcs and bad connections that cause short circuits can be considered as the main causes of PV or BIPV module ignition (Glass for Europe, 2018).

Roof slope, wind load and increased fire load caused by the PV infrastructure (i.e., cables, connectors, mounting system, junction boxes and inverters) are some of the variables that can affect the dynamic fire scenario. Wind load and roof pitch are considered parameters that can be difficult to adjust. At high wind speeds, the concentration of flammable pyrolysis gasses may be diluted to such an extent that ignition is not possible. However, when a fire occurs, the deflection of flames under the modules is assumed to recombine into concurrent flame propagation regardless of wind direction. It is also generally accepted that an essential part of all roof constructions is a slope to ensure drainage of water from the surface. For flat roof constructions, the minimum allowable drop is 1:40 (1:80 for a finished roof). Similar to wind direction, roof pitch can affect initial flame spread, but once ignited the effect is believed to be negligible compared to the consequences of a deflected flame. The cables, connectors and mounting system are known to present an increased fire load on the roof. However, these components are relatively localized and do not cover the entire roof (Allianz Global Corporate & Specialty, 2014; Kristensen et al., 2020).

Materials under the roof membrane are also interesting for the spread of fire for two reasons. First, because of the thermal properties of the insulating materials, which vary depending on the product and temperature. Heat transfer between the lower surface of the roof membrane and the upper surface of the underlying material can affect the heating of the roof membrane. Second, many systems are retrofitted to existing buildings where the roof may not be suitable due to the insulation material. The worst option in this case is a roof insulated only with polystyrene foam. Such a structure will require a layer that mitigates the effects of fire to prevent serious consequences (Kristensen et al., 2022).

In experiments conducted by Kristensen et al. (2022), burning droplets from the bottom end of a tilted PV module were observed. As a result of this continuous dripping, the burning continued. Dripping was observed at the edge of the area where the back foil of the PV panel was burnt. Based on this observation, some PV modules can be considered as a fire load as well as an ignition source because the droplets can also ignite other components. Which can be significant when installing BIPV systems on steep slopes, where dripping can increase the speed of flame propagation downwards, igniting a larger area (Kristensen et al., 2022).

In experiments conducted by Kristensen et al. (2022) also found that the geometry itself made a significant difference in the flame propagation behavior, as the aluminium frame of the PV module blocked the flow of flue gasses, which then formed a layer of hot smoke. The layer of hot smoke had several effects on flame spread. First, it increased the length of the flame spread because the enclosed smoke intensified the preheating. Second, it reduced the flame propagation speed because the smoke layer reduced the effective height of the gap and thereby increased the velocity of the surrounding air (Kristensen et al., 2022).

Photovoltaic modules were also measured in the TÜV Rheinland laboratories, where their response to fire and the rate of heat release during a fire were determined. An internal fire test revealed more damage to the polycrystalline module due to longer and more intense burning of the plastic film on its backside. Damage to the glass was not detected due to the absence of breakage and burning during the test. On the other hand, an external fire test found burnout after 7 minutes. The damaged area is significantly smaller in an internal fire than in an external fire. According to TÜV Rheinland, the behavior of the modules during laboratory tests depends on the configuration and performance of the burner (Prume and Viehweg, 2018).

Furthermore, Kristensen et al. (2022) found that the polymer-based backsheet membrane was burned only at the point of direct flame impact, while the remainder of the backsheet was soiled but intact. Since spontaneous flame propagation does not occur on the PV module, it can be debated whether the PV module itself should be considered as a fire load or rather as an agent of flame propagation (Kristensen et al., 2022)

Based on the findings, it is possible to state that the introduction of a photovoltaic system applied in a building can have more serious consequences in the event of an initial fire on the roof. Based on this, Kristens et al. (2022) proposes to develop a new test method that takes into account the variation in re-emission from a deviated flame. Until then, stakeholders, including property owners and the fire and rescue service, should reassess their fire response, as flame spread to the building envelope is highly likely (Kristensen et al., 2022).

Fire safety requirements

PV panels should not be placed in a fire-hazardous area, i.e., near the windows of the building on which they are installed or near the windows of surrounding buildings so that they cannot cause a fire in the event of their ignition and heat radiation. All envelope structures of buildings with built-in PV systems should meet the required fire resistance and specified limit states. Both the roof and the wall with PV systems should meet the required fire resistance and REI limits (criteria that define the fire resistance of materials). If the PV modules are placed only on part of the roof, the other part should meet the required fire resistance within the limits of (R) EW (Iringova, 2022).

If the PV modules are installed in a sloping roof or perimeter wall, the size of the air gap between the PV panel and the building surface and their slope are decisive from the point of view of the spread of fire along the surface. The narrower the air gap, the faster the surface temperature rises. If the size of the air gap between the PV panels and the building structure increases, the fire will spread faster. In order to prevent the uncontrolled spread of fire on the surface of the building, the building envelope with PV panels should comply with BROOF (t3) (Iringova, 2022). BROOF is a classification designation determining the external fire behavior factor for roofs

The requirements for the surface treatment of roofs and perimeter walls with PV panels in terms of reaction to fire are defined by the fire spread index (Makovicka Osvaldova and Gaspercova, 2015). If the roof has a full-surface installation of PV modules, it should have a non-flammable covering. Thermal insulation in the ventilated roof air gap should also be non-combustible (Iringova, 2022). While the definition of a non-combustible material is directly related to whether a particular material can be used in building systems, the requirements for the properties of a non-combustible material are determined based on various factors such as temperature rise, burning, debris and smoke (Yang et al., 2023).

As an example, fire safety regulations in Switzerland require external walls to be fire-resistant for all residential buildings and buildings taller than 30 m, while low- and medium-rise buildings for other building classifications allow the use of combustible materials (Bonomo et al., 2023).

Demarcation of the fire hazard area around the building has a fundamental effect on the fire safety of the surrounding buildings as well as on the technical equipment and construction of the given building. It is important that this area corresponds as closely as possible to the actual situation. From the point of view of operation and impact on building structures, they are a relatively safe technology that fundamentally does not impair the fire safety of the building. It is worse in the case of a fire in relation to a fire intervention, where there is a high risk of damage to the health of the responding firefighters, as the technologies are still under voltage. From this point of view, it is necessary to take into account the safety of operator movement and fire intervention when designing the building, if the installation of PV panels on its envelope is considered. Therefore, the building envelope should be accessible to firefighters so that they can intervene. It is also necessary to take into account the necessity of movement of firefighters between PV modules during roof installations. If PV modules are installed on a pitched roof, fire access should be incorporated into the building design (Iringova, 2022).

In relation to BIPV fire hazards, fire spread is one of the main fire hazards. There are gaps in appropriate fire prevention and protection measures. As an example, sprinkler systems are installed in selected buildings as a measure to mitigate the spread of fire but cannot stop BIPV modules from producing energy. When a fire spreads to several floors at the same time, the installation of hydrants can also affect the initial intervention, however, people in the building must be able to operate this equipment during a fire. In the same way, BIPV modules that are applied to the facades of high-rise buildings and the vertical spread of fire can limit firefighting from the outside. Therefore, in the context of the mentioned aspects, it is necessary to consider appropriate design and technical measures to mitigate the spread of fire from one fire section to another fire section (Yang et al., 2023).

Another factor that affects fire safety is the so-called hot spots, which arise, for example, as a result of partial shading. This problem occurs with PV panels connected in series. When one of the PV panels is shielded, it becomes a resistance in the circuit and the voltage drop across the shielded cell can produce a huge amount of heat. For this reason, active bypass diodes based on bipolar transistors were developed as a precaution (Ziang et al., 2014). Another practical mitigation measure is the use of module-level power optimizers, which are located on the back of each solar panel (Yang et al., 2023).

5. Conclusion

BIPV systems have a dual purpose as building surface material and energy generator. Although the BIPV industry has developed rapidly in recent years, the fire risk of BIPV applications has been described in several professional publications but is not resolved. The main causes and mechanisms of BIPV fire hazards and impacts are identified as ignition, fire spread and hazards to building occupants and firefighters in the event of an intervention.

In the framework of this article, the intention was to approach the issue of fire safety of BIPV systems, including a warning about the possibility of using international standards such as IEC 61215 and IEC 61730. These standards are used in most countries around the world, with the exception of the USA and Canada, which follow the UL1703 standard. Although international standards are applicable for BIPV modules, the fire safety requirements of BIPV must always comply with national building regulations.

Although studies and research from different countries of the world are presented in this article, the fire hazard of BIPV modules remains, and gaps are visible not only in the mitigation of electrical failure hazards, but also in fire resistance as building elements, including measures to mitigate the spread of fire and prevent module ignition. The publications reviewed in this article point out that electrical faults are the main cause of BIPV fires in buildings, and the fire resistance level determines how fire spreads between PV panels and other building elements.

This is also why it is necessary to focus further on the issue of preventing the spread of fire, to solve measures and innovations in the area of preventing shading, and thus emerging hot spots. It is also necessary to dedicate space for professional training of installers and regular maintenance and inspection. And we cannot forget the firefighters and the firefighting itself, during which it is necessary to take care to eliminate the risk of electric shock. As well as ensuring that, in the event of an evacuation, the persons ensuring the evacuation are not endangered by falling fragments of PV panels or combustion emissions.

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References

Allianz Global Corporate & Specialty. (2014). Fire hazards of photovoltaic (pv) systems. Available online: https://commercial.allianz.com/content/dam/onemarketing/commercial/commercial/pdfs-risk-advisory/tech-talks/ARC-Tech-Talk-Vol-8-Fire-Hazards-PV-Systems-EN.pdf (accessed on 5 October 2023).

Aram M, Zhang X, Qi DQ, et al. (2021). A state-of-the-art review of fire safety of photovoltaic systems in buildings. Journal of Cleaner Production, 308, 127239. https://doi.org/10.1016/j.jclepro.2021.127239

Biyik, E., Araz, M., Hepbasli, A., et al. (2017). A key review of building integrated photovoltaic (BIPV) systems. Engineering Science and Technology, an International Journal, 20(3), 833–858. https://doi.org/10.1016/j.jestch.2017.01.009

Bonomo P, Frontini F, Saretta E, et al. (2018). Fire Safety of BIPV Facades. Available online: https://zenodo.org/records/2564838 (accessed on 18 October 2023).

Bower, W., Quintana, M., & Johnson, J. (2012). Electrical and thermal finite element modeling of arc faults in photovoltaic bypass diodes. Office of Scientific and Technical Information (OSTI). https://doi.org/10.2172/1035329

Chen, T., Yuen, A., Yeoh, G., et al. (2019). Fire Risk Assessment of Combustible Exterior Cladding Using a Collective Numerical Database. Fire, 2(1), 11. https://doi.org/10.3390/fire2010011

Constantinou, S., Al-naemi, F., Alrashidi, H., et al. (2023). A review on technological and urban sustainability perspectives of advanced building-integrated photovoltaics. Energy Science & Engineering. Portico. https://doi.org/10.1002/ese3.1639

Despinasse, M.-C., & Krueger, S. (2015). First developments of a new test to evaluate the fire behavior of photovoltaic modules on roofs. Fire Safety Journal, 71, 49–57. https://doi.org/10.1016/j.firesaf.2014.11.011

Dhere, N. G., & Shiradkar, N. S. (2012). Fire hazard and other safety concerns of photovoltaic systems. Journal of Photonics for Energy, 2(1), 022006. https://doi.org/10.1117/1.jpe.2.022006

Dhimish, M., Holmes, V., Mather, P., & Sibley, M. (2018). Novel hot spot mitigation technique to enhance photovoltaic solar panels output power performance. Solar Energy Materials and Solar Cells, 179, 72–79. https://doi.org/10.1016/j.solmat.2018.02.019

Dhimish, M., Holmes, V., Mehrdadi, B., & Dales, M. (2018). Comparing Mamdani Sugeno fuzzy logic and RBF ANN network for PV fault detection. Renewable Energy, 117, 257–274. https://doi.org/10.1016/j.renene.2017.10.066

Eiffert P, Kiss G. (2000). Building-Integrated Photovoltaic Designs for Commercial and Institutional Structure. Available online: https://www.nrel.gov/docs/fy00osti/25272.pdf (accessed on 4 October 2023).

El-Sherif, N. (2017). Ground-fault protection—All you need to know. In: Proceedings of the 2017 Annual Pulp, Paper And Forest Industries Technical Conference (PPFIC); 18–23 June 2017; Tacoma, United States of America.

European Parliament. (2018). Directive (EU) 2018/2001 of the european parliament and of the council of 11 December 2018 on the promotion of the use of energy from renewable sources. Available online: https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX%3A02018L2001-20181221 (accessed on 9 October 2023).

Gholami, H. (2019). Analysis of solar radiation components on building skins for selected cities. In: Proceedings of the 14th Conference on Advanced Building Skins; 28–29 October 2019; Bern, Switzerland.

Gholami, H., Sarwat, A. I., Hosseinian, H., & Khalilnejad, A. (2015). Evaluation of optimal dual axis concentrated photovoltaic thermal system with active ventilation using Frog Leap algorithm. Energy Conversion and Management, 105, 782–790. https://doi.org/10.1016/j.enconman.2015.08.033

Glass for Europe. (2015). Classification of reaction to fire of glass products Recommendation from Glass for Europe. Available online: https://glassforeurope.com/wp-content/uploads/2018/04/GfE-Reaction-to-fire-Position-Paper_April-2015.pdf (accessed on 18 October 2023).

Guan, R., Jia, Z., Fan, S., & Deng, Y. (2019). Performance and Characteristics of a Small-Current DC Arc in a Short Air Gap. IEEE Transactions on Plasma Science, 47(1), 746–753. https://doi.org/10.1109/tps.2018.2884021

He, W., Zhang, Y. X., Sun, W., et al. (2011). Experimental and numerical investigation on the performance of amorphous silicon photovoltaics window in East China. Building and Environment, 46(2), 363–369. https://doi.org/10.1016/j.buildenv.2010.07.030

Heinstein, P., Ballif, C., & Perret-Aebi, L.-E. (2013). Building Integrated Photovoltaics (BIPV): Review, Potentials, Barriers and Myths. Green, 3(2). https://doi.org/10.1515/green-2013-0020

Humm O, Toggweiler P. (1993). Photovoltaik und Architektur: Die Integration Von Solarzellen in Gebäudehüllen, 1st ed. Birkhäuser Verlag.

Ibrahim, A., Fudholi, A., Sopian, K., et al. (2014). Efficiencies and improvement potential of building integrated photovoltaic thermal (BIPVT) system. Energy Conversion and Management, 77, 527–534. https://doi.org/10.1016/j.enconman.2013.10.033

IER—Institute for Energy research. (2018). A Snapshot of BP's World Energy Outlook 2018. Available online: https://www.instituteforenergyresearch.org/uncategorized/snapshot-bp-world-energy-outlook-2018/ (accessed on 20 January 2024).

Iringova, A. (2022). Location of Photovoltaic Panels in the Building Envelope in Terms of Fire Safety. Civil and Environmental Engineering, 18(2), 523–531. https://doi.org/10.2478/cee-2022-0050

Ju, X., Zhou, X., Gong, J., et al. (2019). Impact of flat roof–integrated solar photovoltaic installation mode on building fire safety. Fire and Materials, 43(8), 936–948. Portico. https://doi.org/10.1002/fam.2755

Ju, X., Zhou, X., Zhao, K., et al. (2017). Experimental study on burning behaviors of photovoltaic panels with different coverings using a cone calorimeter. Journal of Renewable and Sustainable Energy, 9(6). https://doi.org/10.1063/1.4990830

Karda, L., & Kavan, S. (2023). Emergency Board Management as a Tool for Strengthening Resilience of the Electric Power Industry: A Case Study in the Czech Republic. Energies, 16(5), 2467. https://doi.org/10.3390/en16052467

Kavan, Š., Dvořáčková, O., Pokorný, J., & Brumarová, L. (2021). Long-Term Power Outage and Preparedness of the Population of a Region in the Czech Republic—A Case Study. Sustainability, 13(23), 13142. https://doi.org/10.3390/su132313142

Kim, A. A., Reed, D. A., Choe, Y., et al. (2019). New Building Cladding System Using Independent Tilted BIPV Panels with Battery Storage Capability. Sustainability, 11(20), 5546. https://doi.org/10.3390/su11205546

Kodur, V., Kumar, P., & Rafi, M. M. (2019). Fire hazard in buildings: review, assessment and strategies for improving fire safety. PSU Research Review, 4(1), 1–23. https://doi.org/10.1108/prr-12-2018-0033

Kristensen, J. S., Faudzi, F. B. M., & Jomaas, G. (2021). Experimental study of flame spread underneath photovoltaic (PV) modules. Fire Safety Journal, 120, 103027. https://doi.org/10.1016/j.firesaf.2020.103027

Kristensen, J. S., Jacobs, B., & Jomaas, G. (2022). Experimental Study of the Fire Dynamics in a Semi-enclosure Formed by Photovoltaic (PV) Installations on Flat Roof Constructions. Fire Technology, 58(4), 2017–2054. https://doi.org/10.1007/s10694-022-01228-z

Kristensen, J. S., Merci, B., & Jomaas, G. (2018). Fire-induced reradiation underneath photovoltaic arrays on flat roofs. Fire and Materials, 42(3), 316–323. Portico. https://doi.org/10.1002/fam.2494

Kumar, N. M., Sudhakar, K., & Samykano, M. (2019). Performance comparison of BAPV and BIPV systems with c-Si, CIS and CdTe photovoltaic technologies under tropical weather conditions. Case Studies in Thermal Engineering, 13, 100374. https://doi.org/10.1016/j.csite.2018.100374

Masson, G. (2023). Snapshot of Global PV Markets 2023. Available online: https://iea-pvps.org/wp-content/uploads/2023/04/IEA_PVPS_Snapshot_2023.pdf (accessed on 5 October 2023).

Mazziotti, L., Cancelliere, P., Paduano, G., Setti, P., & Sassi, S. (2016). Fire risk related to the use of PV systems in building facades. MATEC Web of Conferences, 46, 05001. https://doi.org/10.1051/matecconf/20164605001

Mohammadi, F., Gholami, H., Nehaj, M. B. (2016). Effect of Ventilation on Yearly Photovoltaic Performance. In: Proceedings of the 2016 International Conference on New Research Achievements in Electrical and Computer Engineering; May 2016; Tehran, Iran.

Mohd Nizam Ong, N. A. F., Sadiq, M. A., Md Said, M. S., et al. (2022). Fault tree analysis of fires on rooftops with photovoltaic systems. Journal of Building Engineering, 46, 103752. https://doi.org/10.1016/j.jobe.2021.103752

Nair, S. S. (2018). A Survey report of the firefighters on fire hazards of PV fire. In: Proceedings of the 2018 IEEE International Conference on System, Computation, Automation and Networking (ICSCA); 6–7 July 2018; Pondicherry, India.

Namikawa, S. (2017). Photovoltaics and Firefighters' Operations: Best Practices in Selected Countries. Available online: https://iea-pvps.org/wp-content/uploads/2020/01/Task_12_Report_Photovoltaics_and_Firefighters__Operations_July_2017.pdf (accessed on 9 October 2023).

Osvaldová, L. M., & Gašpercová, S. (2015). The Evaluation of Flammability Properties Regarding Testing Methods. Civil and Environmental Engineering, 11(2), 142–146. https://doi.org/10.1515/cee-2015-0018

Prume, K., Viehweg, J. (2015). Assessment of the fire risk in photovoltaic systems and creation of safety concepts to minimize risk (German). Available online: http://www.pv-brandsicherheit.de/fileadmin/downloads_fe/Leitfaden_Brandrisiko_in_PV-Anlagen_V01.pdf (accessed on 5 October 2023).

Prume, K., Viehweg, J. (2018). Assessing Fire Risks in Photovoltaic Systems and Developing Safety Concepts for Risk Minimization. Available online: https://www.energy.gov/eere/solar/articles/assessing-fire-risks-photovoltaic-systems-and-developing-safety-concepts-risk (accessed on 9 October 2023).

Rexroth, S. (2001). Designing with solar cells (German). Photovoltaik in der Gebäudehülle, 1st ed. C.F. Müller Verlag.

Schneider, A. (1996). Solar architecture for Europe (German), 1st ed. Birkhäuser Verlag.

Sorgato, M. J., Schneider, K., & Rüther, R. (2018). Technical and economic evaluation of thin-film CdTe building-integrated photovoltaics (BIPV) replacing façade and rooftop materials in office buildings in a warm and sunny climate. Renewable Energy, 118, 84–98. https://doi.org/10.1016/j.renene.2017.10.091

Tripathy, M., Joshi, H., & Panda, S. K. (2017). Energy payback time and life-cycle cost analysis of building integrated photovoltaic thermal system influenced by adverse effect of shadow. Applied Energy, 208, 376–389. https://doi.org/10.1016/j.apenergy.2017.10.025

Voiland, A. (2017). Longyangxia Dam Solar Park. Available online: https://earthobservatory.nasa.gov/images/89668/longyangxia-dam-solar-park (accessed on 5 October 2023).

Wang, C., Ji, J., Uddin, M. M., et al. (2021). The study of a double-skin ventilated window integrated with CdTe cells in a rural building. Energy, 215, 119043. https://doi.org/10.1016/j.energy.2020.119043

Waqar Akram, M., Li, G., Jin, Y., & Chen, X. (2022). Failures of Photovoltaic modules and their Detection: A Review. Applied Energy, 313, 118822. https://doi.org/10.1016/j.apenergy.2022.118822

Weaver, J. F. (2019). There are data missing solar power fires per year. PV Magazine, 23 August 2019.

Wijeratne, W. M. P. U., Samarasinghalage, T. I., Yang, R. J., & Wakefield, R. (2022). Multi-objective optimisation for building integrated photovoltaics (BIPV) roof projects in early design phase. Applied Energy, 309, 118476. https://doi.org/10.1016/j.apenergy.2021.118476

Yang, H. Y., Zhou, X. D., Yang, L. Z., & Zhang, T. L. (2015). Experimental Studies on the Flammability and Fire Hazards of Photovoltaic Modules. Materials, 8(7), 4210–4225. https://doi.org/10.3390/ma8074210

Yang, R., Zang, Y., Yang, J., et al. (2023). Fire safety requirements for building integrated photovoltaics (BIPV): A cross-country comparison. Renewable and Sustainable Energy Reviews, 173, 113112. https://doi.org/10.1016/j.rser.2022.113112

Yin, L., Jiang, Y., & Qiu, R. (2018). Combustion Behaviors of CIGS Thin-Film Solar Modules from Cone Calorimeter Tests. Materials, 11(8), 1353. https://doi.org/10.3390/ma11081353

Ziar, H., Farhangi, S., & Asaei, B. (2014). Modification to Wiring and Protection Standards of Photovoltaic Systems. IEEE Journal of Photovoltaics, 4(6), 1603–1609. https://doi.org/10.1109/jphotov.2014.2344764