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LOCATION OF PHOTOVOLTAIC PANELS IN THE BUILDING ENVELOPE IN TERMS OF FIRE SAFETY

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Abstract

The increasing amount of energy consumed by the operation of buildings results in an increasing environmental burden. This has a direct impact on the innovation of renewable energy technology and its application in building industry. In accordance with the requirements of the "Europe 2020 Strategy" and "Europe 2030 Project", the long-term goal is to achieve the maximum use of renewable energy sources in the buildings´ operation. One of the solutions is the building-integrated photovoltaic power plant. The paper analyses efficiency and incorporation of photovoltaic (PV) systems into the roofs and perimeter walls. PV systems are a renewable energy source used in the construction of zero energy buildings producing minimal environmental pollution. Semi-transparent building-integrated photovoltaics (BIPV) are one of the technologies that have the potential to increase the building´s energy efficiency as well as aesthetically complete the building´s design. The paper deals with material characteristics of PV panels in terms of the fire risk and definition of the fire hazardous area that arises during their combustion. It is focused on the incorporation of various types of PV technology into the facades and roofs, structural and material solutions of fire-dividing structures to which PV systems are fastened considering their location in the fire hazardous area. Based on the external fire simulations, conclusions in this paper bring the optimal position of PV systems in the building envelope in relation to fire open areas, fire lines and fire hazardous areas. The safety of firefighters during the intervention also depends on the position of PV systems. The case study presented in this paper uses a model solution to give the optimal position of PV systems in the building envelope considering the fire safety.

Keywords:

Photovoltaic panels;
Fire risk;
Facade;
Roof;
Renewable energy.

1 Introduction

The long-term main goal of the international communities is to achieve the sustainable development. This issue is currently highly topical in most EU countries due to the ongoing energy crisis.

The 1992 Earth Summit document sets the principles for sustainable development in terms of social, environmental and economic growth.

The "Europe 2030 Strategy“ defines the requirements for sustainability in the construction and operation of buildings, including their demolition. One of the main goals of the EU's investment strategy is to tackle climate change by reducing greenhouse gas emissions and fossil fuel consumption and provide reliable, sustainable, modern and affordable energy for the operation of buildings so as the carbon neutrality would be achieved by 2050. In line with this strategy and the Renewable Energy Directive (RED), the goal is to cover 32 % of energy consumption from renewable sources [1]. These requirements can only be met through the active use of such technologies in buildings that would obtain energy primarily from the renewable sources and subsequently would be able to transform it for the operational needs. Solar energy is the most available source that can

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provide energy for optimizing the thermal microclimate and operating technical equipment in buildings during their construction in our climatic conditions. To transform it into electricity using PV panels, it is possible to install them on the external surface of buildings. Solar radiation is the unlimited and most affordable source of renewable energy. If the potential for the use of it from the radiated surfaces of buildings with incorporated PV modules increases, there will be a significant independence from the non-renewable energy sources and reduction of environmental burden.

The current problem of the electricity production using PV modules is a high cost associated with its transport to the place of consumption. Therefore, it would be ideal to construct building-incorporated photovoltaics (BIPV) at the point of consumption. BIPV systems consist of photovoltaic cells incorporated into the building envelopes, such as roofs or facades. Such system has two functions:

1) It is the final construction-material solution of the building envelope itself having the function of weather protection, thermal, acoustic and fire insulation.

2) It provides electricity for the building´s operation.

If the building is renovated, PV systems are fastened to the auxiliary load-bearing structures anchored to the existing building envelope, most often to the roof. They are called building-applied photovoltaics (BAPV). Both systems become the building's energy generator [3, 4]. BIPV and BAPV systems supply energy where the end user consumes it. Generated direct current is stored in a battery or it is forwarded into the public electricity network. It is ideal to store energy in batteries directly in the building to cover the night's electricity consumption for heating, cooling or artificial lighting.

PV panels incorporated into the building envelopes appear as an ideal solution in terms of the environmental impact because the generator is at the place of the energy consumption and its installation does not need to take the agricultural land [5, 6]. PV systems within the building envelope can be considered as open technological devices for the production and transformation of direct current. The production of PV panels and other components uses flammable materials, which affects the fire risk degree. Therefore, it is necessary to respect their fire characteristics and specifics if they are incorporated into the building envelope because they have an impact on the fire course and extinguishing.

1 Application of PV systems in the building envelope

PV systems can be divided into building-applied photovoltaics (BAPV) and building-integrated photovoltaics (BIPV). BAPV systems are usually fastened to a frame structure on the building envelope in various arrangements. It is important to pay attention to their inclination, solar surface, production technology and orientation to the cardinal points. Placed on facades and roofs as additional devices, they represent a solution suitable for the reconstruction of energy systems in modernized buildings, Fig. 1.



Fig. 1: BAPV systems fastened to the building envelope (Source: Internet).

BIPV systems are the optimal solution for new buildings. PV panels are incorporated into the building envelope and external supplementary structures. Their effective area is usually larger than in BAPV systems. They are often used in the all-glass facades oriented to the south, southeast or southwest in the urban areas with a low degree of external shading by the surrounding buildings.

They can be incorporated into the shading lamellas of sunshades, balcony railings, awnings and the like. It is also possible to apply them in large skylights and atrium glass roofs, or use them to replace the classic covering of sloping roofs. If BIPV systems are applied in a general renovation of the building envelope, it is possible to achieve the energy efficiency of a zero energy building (ZEB), or even plus energy building [7, 8]. As for the elements used, they can be applied as foil tiles, modules and glazing made from solar cells. The application of BIVP systems in the building envelope is shown in Fig. 2.

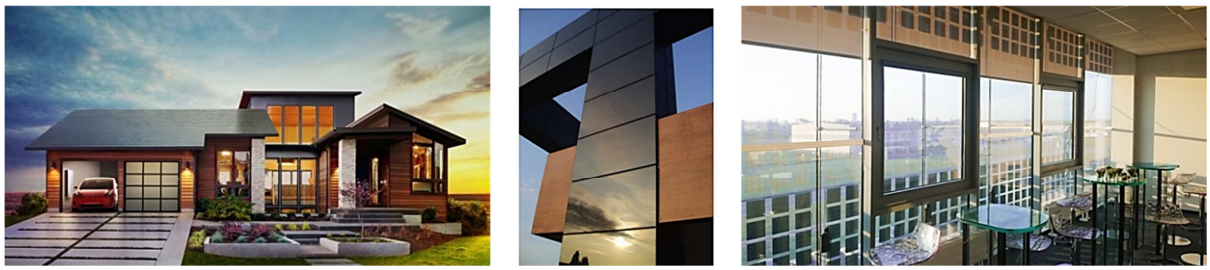


Fig. 2: BIPV applications in the building envelope (Source: Internet).

PV systems can also be implemented as the photovoltaic thermal systems (PVT) with active or passive ventilation behind the panels and subsequent redirecting of the hot air into the heating system. PV modules are cooled down using air or water [9-11] so the production of electricity and heat in a building is more effective [12-14]. For example, BIPV ventilated in the air gap of a double-skin facade or roof has the PV system typically installed in front of the interior skin of the building envelope. The backside of BIPV is naturally ventilated and cooled down by the fresh summer air increasing the efficiency of electricity generation. If BIPV uses this extracted hot air for heating, it will change into a new configuration called building-integrated photovoltaic thermal system (BIPVT). Experimental assessment of the thermal efficiency of the BIPV ventilated wall is given in the study by Chiu, M. S. - Hou, S. P. - Tzeng, C. T. - Lai, C. M. [15]. Examples of the building facades using different energy production throughout the day can be found in [16-18]. The application of BIPV is not limited only to a building; it can also be used in vehicles such as ships, cars, or planes contributing to their optimal performance in terms of the energy consumption.

2 Material characteristic of PV systems

Based on the solar cell composition and connection to the power network, PV systems can be separate with accumulation into batteries, connected to the public power network, or hybrid, i. e. combination of the previous two systems. There are various technologies of PV modules available. Thin-film technologies that have the highest efficiency up to 18 % are divided into polycrystalline silicon and monocrystalline technologies.

PV panels can have crystalline silicon cells, monocrystalline gallium arsenide (GaAs), thin-film technologies and multi-cord cells. Monocrystalline and multicrystalline are the two basic forms of crystalline technology. Compared to all other types of PV technologies, the crystalline silicon technology is the most frequent one in the construction market. The crystalline silicon C-Si can be used as a mono- or polycrystal. The monocrystal is slightly more efficient than the polycrystal, but the performance of the panel is highly dependent on the incidence angle of sunlight, i.e. the bigger the diversion from the ideal perpendicular incidence angle, the lower the energy performance.

The performance of a polycrystalline panel is less dependent on the ideal (perpendicular) incidence angle of sunlight. Monocrystals and polycrystals have a higher temperature dependence on the ambient temperature and the electrical parameters of the panel change more significantly.

Amorphous silicon PV panel cells - thin-film panels are based on a-Si (amorphous silicon), CdTe (cadmium telluride), CIS (coper, indium, and selenium), CIGS (coper, indium, gallium, selenium). They are less energy efficient than crystalline silicon, while their performance is less dependent on maintaining the ideal perpendicular incidence angle of sunlight and have a lower temperature dependence on climatic conditions. Hybrid panels are a combination of crystalline and amorphous panels. Biotechnological solutions are used in specific cases. Their reaction to fire depends on the components used.

PV panels can have a frame construction with PV cells placed in a solid, usually aluminium frame. This solution is most common in BAPV systems. BIPV systems have no frame panels so they can be incorporated into the facade. Flexible panels are used in specific cases such as round surfaces, railings, shading slats, etc. Solution examples of the abovementioned constructions are shown in Fig. 3.



Fig. 3: Solutions of PV panel construction (Source: http://www.neosolar.cz/userfiles/image/eva%20folie%202.jpg).

PV modules consist mainly of non-combustible materials such as glass - 3, photovoltaic cell - 5, aluminium frame - 1, combustible foils - 4 and 6, seals - 2, see Fig. 4.

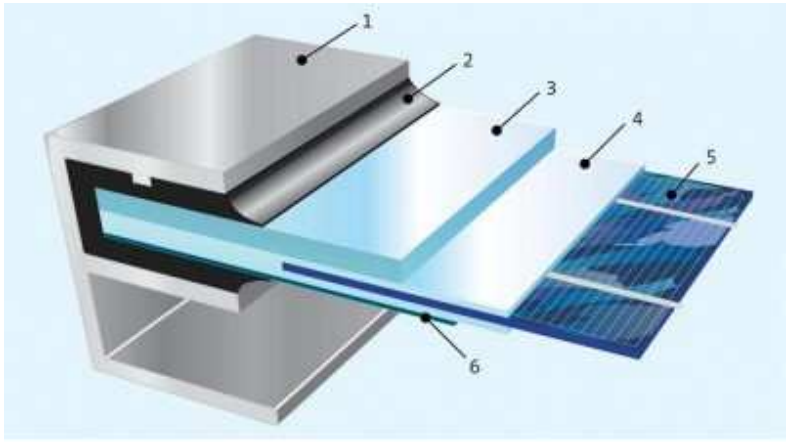


Fig. 4: Material composition of PV panels (Source: http://www.neosolar.cz/userfiles/image/eva%20folie%202.jpg).

3 Fire risk of PV systems

Measurements of PV modules taken by TÜV Rheinland e. V. in cooperation with Current determined their reaction to fire and the heat release rate during fire. Partial results from this test are shown in Figs. 5 and 6.

The fire reaction test depends on the burner performance, thermal stress configuration (at the top or bottom of the panel) and on the inclination angle of the panel. The internal fire test detected bigger damage to the polycrystalline module due to the longer and more intense burning of the plastic foil on its back. Glass damage was not detected due to the absence of its breaking and burn-through during the test. On the other hand, the external fire test detected burn-through after 7 minutes. The damaged area is significantly smaller in internal fire than in external fire. Behaviour of the modules during laboratory tests depends on the burner configuration and performance [23]. The test simulates external fire conditions.

The fire test revealed that PV panels are flammable devices and can cause fire in a building. The intensity of heat radiation at the time of fire is relatively low so PV panels are not risk for fire spreading. The boundary of the fire hazardous area for the critical fire scenario with the thermal radiation of 18.5 kW/m^2 from the PV panel inclinated at 23° is about 1 m. According to DIN 4102, PV panels are usually classified as B2 or B1. It is not possible to classify them as A just because their module composition contains plastic.

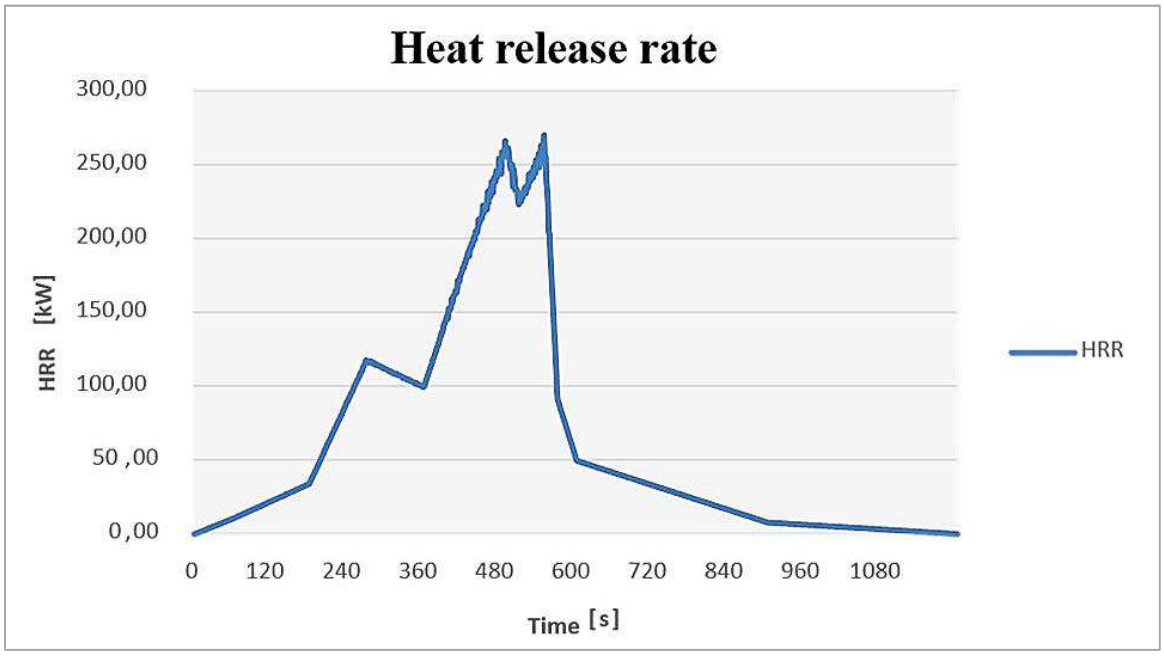


Fig. 5: Heat release rate according to CFD model (tested by TUV-Rheinland) [23].



panel C-Si *panel CIS* *panel CdTe*

a) PV panels damaged using the 25 kW burner.



panel C-Si *panel CIS* *panel CdTe*

b) PV panels damaged using the 150 kW burner.

Fig. 6: PV modules damaged during the test using 25 kW and 150 kW burners causing inside fire in the Si (polycrystalline) high-colour module, CIS and CdTe panels. The data are taken from the fire test of PV panels carried out by TÜV Rheinland e.V. in cooperation with Current [23].

4 Location of PV systems in the building envelope in terms of fire safety

4.1 Legislation

Currently, there are no special fire safety regulations for the PV system design within the building envelope in Slovakia. EU countries use their national guidelines for both designers and firefighters.

The principles of PV system location in the roof were taken from the document „Photovoltaics and Firefighters' Operations: Best Practices in Selected Countries". Photovoltaic systems, VdS 3145: 2017 - 11 (02). This regulation is valid in EU [2].

Requirements for building envelope structures - their fire resistance and fire reaction - are defined in accordance with Regulation 94/2004, considering the fire characteristics determined by the fire test of the PV module carried out by TÜV Rheinland e.V. in collaboration with Current.

4.2 Fire safety requirements for the building envelope with installed PV systems

According to valid Slovak legislation, PV panels are classified as flammable devices so they must not be located in a fire-hazardous area, i.e. near the windows of the building on which they are installed or near the windows of the surrounding buildings so that they could not cause fire in case of their ignition and heat radiation. Therefore, it is not possible to install them in the location of vertical and horizontal fire lines. This limitation does not need to be applied if the building´s fire height and functional use meets the condition of no fire lines on the facade between the fire sections. All building envelope structures with incorporated PV systems must meet the required fire resistance and determined limited states. The roof and wall with PV systems must meet the required fire resistance and REI limits. If PV modules are located only on a part of the roof, its other part must meet the required fire resistance within (R) EW limits.

If PV modules are installed in the sloping roof or perimeter wall, the size of an air gap between the PV panel and building´s surface and their slope is crucial in terms of fire propagation across 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 building structure increases, fire will spread more quickly. In order to prevent the uncontrolled fire spread across the building surface, the building envelope with PV panels is required to meet B_{ROOF} (t3).

The requirements for the surface treatment of roofs and perimeter walls with PV panels in terms of fire reaction are defined by the fire propagation index [19-22]. It must be 0.0 mm/min in this case. If the roof has full-area installation of PV modules, it must have a non-flammable covering. The thermal insulation in a ventilated roof air gap must also be non-flammable.

4.3 Fire hazardous area

The thermal radiation intensity from PV panels depends on the fire source intensity. The abovementioned laboratory measurements of PV panels proved that the fire hazardous area is about 1 m; using a 150 kW burner at the maximum heat release rate HRR and 18.5 kW/m^2 heat flux. The test was focused on PV panels installed on the floor at an inclination angle 23° [23] and the results indicate that PV panels are not a major risk of fire propagation on the building´s surface.

Currently valid Slovak legislation dealing with assessment of the fire hazardous area around PV systems works on the assumption that it is an open technological device, as PV panels are devices that produce electricity and are still live during the day. The fire hazardous area is determined according to Regulation 94/2004 and STN 920201-4 and is uniform for all types of open devices. According to these criteria, the required distance is 6.5 m. The fire hazardous area defined in this way is significantly larger and there is a critical thermal radiation, as laboratory tests found, Fig. 7.

Defining the fire hazardous area around the building has a major impact on the fire safety of surrounding buildings as well as on the technical equipment and construction of the designed building. It is important for that area to fit the real situation as much as possible.

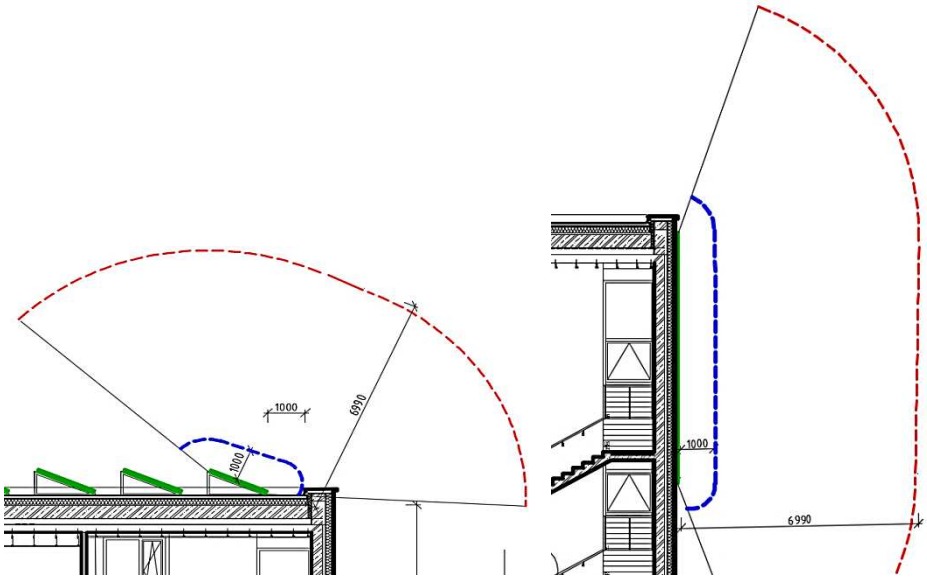


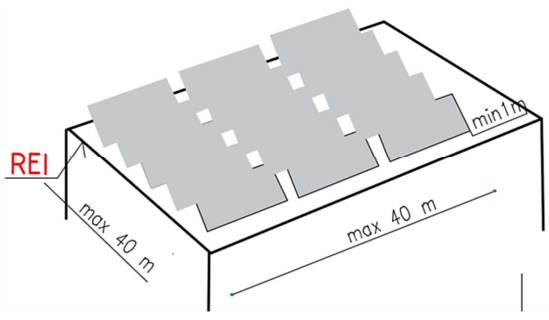
Fig. 7: Defining the fire hazardous area and its comparison in terms of Slovak legislation and fire test results.

The most common source of fire in PV technologies are errors in their installation, or in times of extreme climatic conditions - lightning strikes, mechanical wind damage and subsequent short circuits.

In terms of operation and impact on building structures, they are a relatively safe technology that does not fundamentally worsen the fire safety of the building. It is worse in the case of a fire in relation to a fire operation, where there is a high risk of damage to the health of the firefighters intervening, as the technologies are still live. 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 in its envelope is considered.

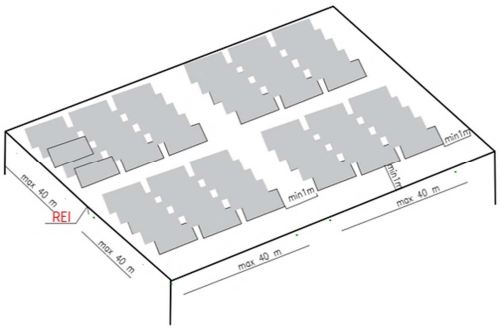
5 Fire intervention requirements for the location of PV systems

The building envelope must be accessible for firefighters so as they would be able to intervene using fire hoses. The flat roof must be accessible via interior protected staircase or, in the case of buildings with a low fire height, via fire ladder. It is necessary to take into account the need for firefighters to move among PV modules. The requirements for building structures, structural solutions and location of PV modules up to 160 m^2 on flat roofs are shown in Fig. 8a. The requirements for locating PV systems over 160 m^2 are shown in Fig. 8b. If PV modules are installed on a sloping roof, the fire access should be incorporated into the building design. Examples of fire access to PV modules located on one or both sides of a roof are shown in Fig. 9.



a)

- The roof must meet B_{ROOF} (t3) requirements to minimize the fire propagation risk.



b)

- The roof must meet B_{ROOF} (t3) requirements to minimize the fire propagation risk.
- The exterior fire intervention routes must be provided.
- The electrical cabling must be protected.

Fig. 8: Fire intervention requirements for PV modules situated on a flat roof.

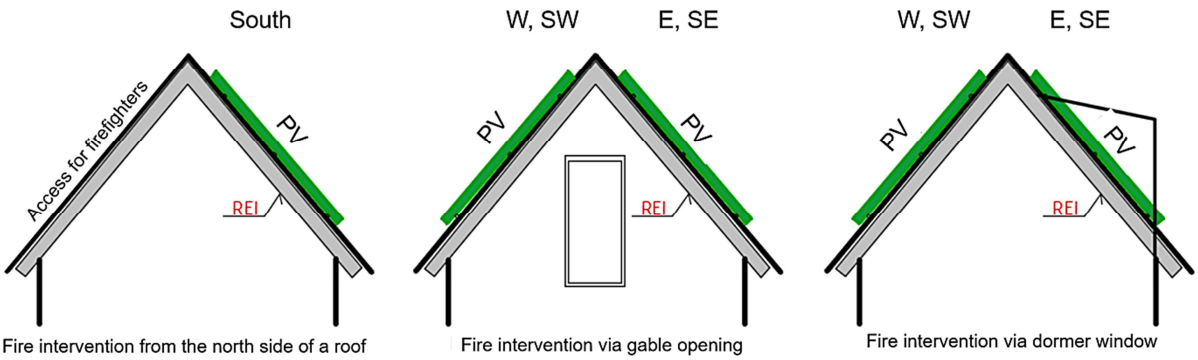


Fig. 9: Fire intervention requirements for PV modules situated on a sloping roof.

6 Conclusion

Nowadays, the offer of PV technology opens a wide space for its use in the building envelope. When applied without frame systems, PV panels can be incorporated into both building envelope and additional structures - railings, sunshades, etc.

PV panels incorporated into the building envelope are necessary to be designed with respect to the increased fire resistance requirements for the structures on which they are installed. It is also needed to take into consideration the fire propagation index.

As for the operation and impact on building structures, PV panels represent a relatively safe technology that does not worsen fire safety of a building. The problem can be in the fire intervention because there is a high risk of health damage to firefighters, as PV panels are still live. If the installation of PV panels in the building envelope is designed, it is necessary to take into account the safety of operator´s movement and fire intervention as well as the location of backup batteries and control devices so that they would be easily accessible to firefighters at the time of fire intervention.

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