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Factors Affecting the Fire Safety Design of Photovoltaic Installations Under Performance-Based Regulations in Norway

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Abstract. The impact of Photovoltaic (PV) installations on the fire safety of buildings must be considered in all building projects where such energy systems are established. The holistic fire safety of the building largely depends on how the fire safety of the PV installation is considered by the different actors during the design and construction process. Research has therefore been undertaken to study how performance-based regulations in combination with the lack of national guidelines affect the overall fire safety considerations for PV installations in Norway. Four factors were found to govern to which extent PV installations are emphasised in the fire safety design phase: (1) whether the building was first of its kind as a pioneering building, (2) whether the building was built before or after the publication of the 2018 revision of the norm NEK 400, (3) The level of knowledge and experience of the fire safety consultant, which in turn affects the use of performance-based engineering tools and the level of detailing in the design and construction phases, and (4) The degree of integration in the building. The main goal of the study is to give an insight and a contribution to the development of in-depth knowledge on how fire safety design for PV installations on buildings is handled in Norway, which may also be relevant to other countries with similar performance-based regulations.

Keywords: Photovoltaic, PV installations, Fire safety engineering, Fire safety design, Performance-based regulations, Energy efficient buildings

1. Introduction

According to the European Directive on energy performance of buildings, all new buildings in EU countries must be nearly zero-energy buildings (NZEB) from the end of 2020 [1]. The use of renewable energy sources in the building sector is essential to obtain this goal. Photovoltaic (PV) installations are one of the fastest-

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growing renewable energy technologies on the market and has a considerable potential for energy production. PV installations can be implemented on both new and existing buildings, as an external installation or integrated in constructional elements like facades and roofs. Currently, there are two primary types of PV systems [2]: BAPV (Building Applied Photovoltaic) are PV systems installed outside the completed façade or roof and has no other function than to produce energy. BIPV (Building Integrated Photovoltaic) are PV systems integrated into the façade or roof of the building, replacing external façade cladding, roofing or other constructional elements. As opposed to BAPV, BIPV replaces conventional materials in the building envelope and must also fulfil other properties like weather protection and snow loads. The increasing focus on reducing material use and the growing demand for more architectural freedom and seamless integration makes BIPV attractive to be applied to an expanding number of buildings.

However, the use of PV installations on buildings poses certain specific challenges, including different issues related to fire safety design: The installation of PV panels introduces several electrical components to the buildings envelope which may increase the fire risk in terms of overload and short circuit [3, 4]. In case of fire start in a PV module, the fire can spread over several PV modules, large façades, or roof areas and eventually inside the building, causing extensive damage and loss of property. Fumes from the fire can enter the building through openings like windows or ventilation systems and cause harmful conditions for the people in the building [5].

With a growing number of PV systems installed on buildings, an increasing number of fire incidents have been reported. According to Italian National Firefighters Brigade, per 2016 there had been about 1600 fires related to PV installations in a total of nearly 590.000 PV plants installed and operating in Italy, which is approximately 0.3% of the plants [6]. A study conducted in Germany from 2011 to 2013 found that 430 cases of fire or heat damage were reported among 1.3 million PV systems. Among those damages, about half of the cases were caused by PV systems and the other half by an external source. Available statistical data from Australia (2009–2015), Germany (2008–2012), Italy (2008–2015) and the USA (2009–2018) was analysed by Mohd Nizam Ong et.al. [7] where the global annual number of PV related fires was calculated to 0.0289 fires per MW. There were large differences between the four countries, which to a large extent was caused by differences in the statistical data collection, but differences in regulation and installation practices may also have contributed to these differences. A review on the fire safety of PV systems in buildings conducted by Aram et al. [8] provides further examples. According to this study, PV-related fires can be caused by physical failures (cell damage, crack, degradation), environmental failures (dust and shading) and electrical (hotspot, mismatch, arcing, ground, line-line) failures. Pandian et al. [9] investigated partial shading in PV cells and found that hotspot is a potential source of ignition. There is also other recent research dedicated to other aspects of PV fires. Chow et al. [10] studied the fire behaviour of two commonly used PV panels under radiative heat fluxes and found that thermal hazards where low, while vast quantities of smoke were emitted under high heat fluxes. Cancelliere et al. [11] developed new test protocols focused on PV roofs' fire rating and found that the deterioration of modules tested (thermal cycling, humidity, mechanical stress, etc.) has not produced significant results on the modules' fire rating. The growing number of PV installations and fire incidents and the causing factors identified suggest that more knowledge about fire safety design of PV installations on buildings is crucial to develop fire safe buildings with PV installations.

Fire safety design is, in many countries like for example Norway, UK and New Zealand [12], managed through a performance-based building regulatory system. The principle of performance-based fire safety design is to design and construct a building to meet a set of fire safety objectives, specified in functional requirements and quantified in specific performance criteria [13]. These performance criteria are challenged by a selected number of design fire scenarios, which must cover both likely and, to a certain extent, less likely conditions that may occur in the building [14]. The description of design fire scenarios and fire conditions that may occur is however dependent on the experience and competence of the person performing the analysis and the level of risk they identify for the different installation aspects [15–17]. In Norway there is no jurisdiction or formalized process that govern someone using the term engineer or specifically fire protection engineer. Hence, the level of competency, knowledge and practice behind the fire safety design might be highly variable. The current practise in Norway, here represented by all Nordic countries, is also commented upon by Bjelland and Njå. They state that "Current fire safety engineering practice shows that the risk concept is not commonly adopted by fire safety engineers" [18], even though the risk assessment is a fundamental part of fire safety engineering in performance-based fire safety design.

Performance-based building regulations were introduced in Norway in 1997, and the intention was to allow for new concepts and building methods, solutions, materials, and products, permitting both prescriptive and performance-based engineering solutions [19]. This change opened for an extended use of and new areas for risk based and analytical fire safety engineering, using methods like hand calculations and numerical simulations for smoke spread, crowd movement and fire resistance. 10 years after the introduction, Stenstad and Bjørkmann pointed at problems with the lack of verification methods, and that the results of the fire safety analysis were to a large extent dependent on the subjective judgement of the fire safety engineers and could vary greatly between engineering companies [20].

The current regulation, TEK17, was implemented in 2017 [21]. TEK17 specifies fire safety requirements for technical installations in general but has not been revised or updated in correlation with the development of PV systems used on buildings and does not cover PV systems or other energy generation and energy storage systems. As an example, the building regulations requires sufficient arrangements for the fire service, but no individual requirements are made in cases where PV modules or battery banks are installed in the building. The building authorities have developed a prescriptive guideline with pre-accepted solutions that comply with the regulations [22]. However, pre-accepted solutions for PV systems are also lacking here. This study of the factors affecting the fire safety design of PV installations focuses on Norway due to the nations lack specific regulations governing all aspects of PV installations in buildings. The number of PV installations in Norway are to date relatively low with only 0.1% of the total electricity generated by PV as compared to 5% globally and 7.2% in EU [23]. This suggests that the experience in designing and building PV installations on buildings is relatively low in Norway.

Depending on the type of PV installation, different regulations apply; BAPV installations are considered electrical installations and therefore controlled by the *Regulation on electrical low voltage installations* (FEL) [24], in which a collection of prescriptive standards, NEK 400 [25], are referred to as a method to fulfil the requirements given in FEL. BIPV installations on the other hand, are considered as building products prerequisite to the building's functionality, and hence must fulfil functions like structural integrity, durability to weather exposure, water tightness and fire safety. BIPV installations are therefore, in addition to FEL, regulated by the performance-based building regulation TEK17 [21]. In addition, BIPV modules used on facades are regulated by the Norwegian standard NS 3510 [26] on safety glass in construction works, which requires the same level of safety and quality for glass used in the BIPV modules as other glass panes used on facades.

The lack of common regulations for BAPV and BIPV installations in Norway, which also consider the underlying building construction, may give different detailing levels of fire safety design for buildings that initially have the same risk level. In addition, lack of communication and poor information transfer between the different disciplines involved in the design and construction phases may result in insufficient fire safety design [27]. The design and construction phases are strongly interdependent yet performed largely separately with varying degrees of communication between them. Consequently, to develop fire safe PV installations on buildings, it is essential to understand how the different disciplines consider the fire safety of the PV installations during the design phase and construction phase and which factors affect the level of detail. There is also a lack of national guidelines for PV installations in Norway covering all aspects of the PV installation process but there are several international guidelines already available, such as the Italian national fire services guidelines [6] and solar electricity safety handbook for firefighters in Canada [28]. More information concerning different guidelines can be found in a recent review [29]. However, the guidelines found internationally does not take into account the Norwegian architectural traditions and weather conditions like snow, ice and low temperature ranges.

Three key prevalent challenges have been identified in the literature related to fire safety aspects of PV installations on buildings: (1) the change in fire dynamics when introducing a PV module to a building envelope; with a potentially faster spread of flames and higher temperature in the gap between module and underlying surface [30, 31], (2) the lack of international harmonisation of existing test standards and the lack of suitable test standards for documentation of fire safety on a system level, particularly regarding BIPV [32, 33], and (3) insufficiencies related to the fire safety design of PV installations in buildings, including considerations related to ignition, fire spread and firefighting [3]. The two latter issues are investigated in the present study.

This paper aims to establish a better insight into and contribute to the development of in-depth knowledge on how fire safety design with respect to PV installations on buildings is handled in Norway and reveal the main factors affecting the fire safety design of PV installations. Performance-based regulations and PV installations are both in their early development. An important goal is to understand whether the different disciplines have a mutual understanding of how and to what safety level the fire safety design should be carried out. Variations in definitions of risk levels and hence added safety measures could cause variations in the added building cost. This may, in turn, influence the market uptake of PV installations on buildings, both in Norway and countries with similar regulations. The study is carried out as a qualitative analysis consisting of semi-structured interviews of professionals with practical experience within PV installations in Norway and a case study including five different buildings with PV installations.

2. Methods

2.1. Qualitative, Semi-Structured Interviews

Five qualitative semi-structured interviews were carried out as an initial action to map how fire safety design with respect to PV installations are handled by different stakeholders during the building process, concerning both the technical installations and the underlying building construction. Interviews as a part of the research method were chosen because it allows to explore details in the different building phases based on the interviewee's thoughts, experience and opinions, which helps to gain more in-depth information. Semi-structured interviews allow for both closed- and open-ended questions in one-to-one interviews, and they are suitable for interviews where the answers often require follow-up queries [34]. The number of informants in this study is low and is only intended as an indicative measure to see if the findings from the literature study is confirmed by stakeholders in the industry.

The interview objects were all key informants from Norway and were chosen broadly to cover the whole building process, including one consultant electrical engineer specialised within solar systems, two consultant fire safety engineers, one building contractor and one representative from the fire service. The key informants were chosen based on their knowledge and understanding of PV installations and fire safety issues, in order to provide a good insight on the nature of the problems discussed in this study. A semi-structured interview guide was designed based on two of the key challenges identified from issues prevalent in the research literature [4, 32]: lack of harmonised standards and test methods for the fire properties of PV systems, and insufficient knowledge on fire safety design of PV systems. The main topics within both key challenges were the following:

1. Technical measures to reduce the fire risk of PV installations.
2. Structural aspects of the building.
3. Arrangements for the fire service.

Table 1
The Topic Guide of the Semi-Structured Interview Schedule

Technical measures to reduce the fire risk of PV installations
•How can common fire causes be prevented? Key words: earth faults, lightning systems, arcing, short-circuiting, etc
•What are relevant standards and fire prevention measures for BIPV installations?
•Is there a need for a shutdown switch used by the fire service?
•Are power optimisers to reduce the DC voltage used?
•How to handle the fire risk related to cable routings and connectors?
•What is the estimated life expectancy for components with respect to fire safety?
Structural aspects of the building
•The lack of international and national regulations – are the guidelines clear enough?
•How are cable penetrations through fire separating building elements handled?
•What is the fire separating requirements for inverter rooms?
•How is the use of combustible insulation in combination with PV installations handled?
•Are there any special measures or demands for roofing material used in combination with PV installations?
Arrangements for the fire service
•What technical and organisational measures to reduce the risk for the firefighting crew are implemented? (shutdown switch, power optimisers, floor plans for orientation with marking of PV components, etc.)
•Are there any problems identified in relation to the need for cutting through the roof elements to ventilate fire gases?
•How do you handle the use of water for extinguishing and the risk of arcing?
•Is there a focus on marking of PV components?

Table 1 shows the interview structure used to guide data collection throughout the whole survey. All the interviews were performed by the same investigator and were arranged as physical meetings or by telephone. The duration of the interviews were approximately 60 minutes by average. Data were noted down during the interviews and transcribed the same day to give the most accurate detail rendition. No audio recording was made. The transcriptions were then checked by each interview object for consistency. Finally, the results were systematised and analysed.

2.2. *Qualitative Design Review of the Case Buildings*

Five case buildings involving BAPV or BIPV installations were investigated with the purpose to highlight differences in the design and practical solutions, in order to obtain a deeper understanding of the different fire safety measures chosen for each individual building. Special attention was given to documents developed in the design phase, if and how the fire safety measures have been pursued in the construction phase, and to what extent factors such as the building construction and firefighting measures have influenced the choices made. The fire safety design methods used are not the focus of this study and are therefore not investigated. The focus is on the fire safety measures related to the PV systems only, e.g. fire start in PV, fire spread in the PV, fire spread to or from the PV system. The case buildings were selected due to their large PV installations, the availability of information related to fire safety aspects, and to illustrate diversity of fire safety measures and fire safety engineering approaches. The case buildings are:

1. ZEB Laboratory, Trondheim, Norway
2. Heimdal Upper Secondary School, Heimdal, Norway
3. Powerhouse Brattøra, Trondheim, Norway
4. Kiwi Dalgård, Trondheim, Norway
5. Spar Snarøya, Bærum, Norway

The three first buildings have an expressed goal of high energy efficiency from an early stage in the engineering process, leading to the implementation of large PV installations and innovative solutions. In this study we have defined these buildings as pioneering buildings, which are first of its kind in terms of innovative solutions and design, large extents of PV installations on roof and walls, new and innovative building materials, and which often holds an environmental certification like BREEAM or similar. Such certification is issued based on high scores on energy, water, transport, health, recyclable storage and construction impact management credits [35].

The two last buildings are designed with a green building profile, which includes PV installations, sustainable building materials, and other environmentally sound solutions. These buildings do not have a BREEAM certification or similar.

A qualitative design review of the five case buildings has been performed. The review includes studies of the as-built fire safety concepts to identify differences in safety measurement levels and to what extent the PV installations have had a direct influence on the fire safety measurements made. The fire safety methods applied in the development of the fire safety concepts for the case buildings are extensively based on pre-accepted solutions where the deviations are evaluated based on qualitative and quantitative analyses. In addition to studying the fire safety concepts, the design review was based on dialogue with relevant stakeholders, such as the fire service, fire safety consultant and building owner. Information on structural aspects for each building is given below.

2.2.1. Structural Layout of ZEB Laboratory The ZEB Laboratory is a zero-emission building located in Trondheim, Norway [36]. The supporting documentation reviewed for this case building included fire safety premises, verification of fire safety concept and fire safety assessment of deviations from NEK 400 [25].

The ZEB Laboratory is a combined office and education building for research purposes, where facades, structural components and technical systems may be changed or substituted in accordance with the research project ongoing at the time. The building is classified as a ZEB-COM building, which implies that the sustainable energy production on the building site is planned to compensate for all emissions from construction (C), operation (O) and materials (M) over a lifespan of 60 years [37]. The building was completed in 2020.

For optimal energy harvesting BIPV systems are used as roofing on the entire roof surface, and as external cladding on large areas of the east, west, and south facades, and a small area on the top of the north façade. Dummy modules with the same shape and colour as the PV modules are used for aesthetical purposes on parts of the roof and facades not covered by PV modules. A total of 701 PV modules, with an area of 963 m^2, are installed on the building. The installed BIPV system has an expected total peak production effect of 181 kW, including the modules on both the roof and facades when the sun is at its optimal position.

The roof of the building is constructed as an unventilated timber-frame roof with a slope of 32° and a span of 20 m. BIPV modules are mounted as a ventilated roofing with an air cavity of 126 mm between the BIPV and a roofing membrane. The complete roof construction consists of, from the inside: gypsum board cladding, smart vapor barrier, glue-laminated beams (glulam) and I-beams, loose-fill glass wool insulation between the beams, wooden sheathing (plywood), roofing membrane, wooden battens and BIPV modules. Because the roof construction is performed as a compact sloping wooden roof with a long roof length and has a smart vapor barrier as a part of an experimental study, a roofing membrane has been added under the BIPV modules as an extra safety measure to reduce the possibility of water leaks. See picture on the left in Fig. 1. The roof's load-bearing structure is designed with a fire resistance of 60 minutes, i.e. R 60 in accordance with EN 13501–2 [38].

On the façades the panels are mounted as a ventilated cladding on a combination of metal and wooden battens. The exterior walls are constructed as timber-frame walls with, from the inside: gypsum board cladding, interior vapour barrier, timber-frame with mineral wool insulation between the studs, exterior wind barrier, wooden and metal battens, BIPV modules. See picture on the right in Fig. 1.

2.2.2. Structural Layout of Heimdal Upper Secondary School The new Heimdal Upper Secondary School was opened in 2018 [39]. The supporting documentation reviewed for the school consist of the as-built fire safety concept that was made available, and communication with the building owner.

The school is a pilot building in the ZEB Research Centre on Zero Emission Buildings and its ambition is to achieve ZEB-O20%M [37]. Hence, all greenhouse gas emission associated with operation of the building and 20% of the material emissions should be compensated through energy production on-site. The total heated floor area of the school building is 18 675 m^2 and a connected sports hall is 7681 m^2, distributed over a total of 6 floors. The school accommodates 1140 students, and the sports hall has a capacity of 4000 people. The roof is constructed using roof elements made from plywood, steel profiles and mineral wool insulation. It is a gable roof that is sloped 2.80° and 4.19° towards north and south, respectively. The total surface area of the roof is 4000 m^2, whereof 1937 m^2 (44%) is available for the PV installation [40]. A BAPV system was chosen for this roof. The installation as built deviated slightly from the information found in the fire safety concept. According to information from the PV contractor, the PV modules are installed on top of the roof as seen in Fig. 2, with a total of 1200 PV modules giving a combined installed peak power of 414 kWp under standard test conditions. The 1200 modules are connected in 100 strings, each with 12 modules.

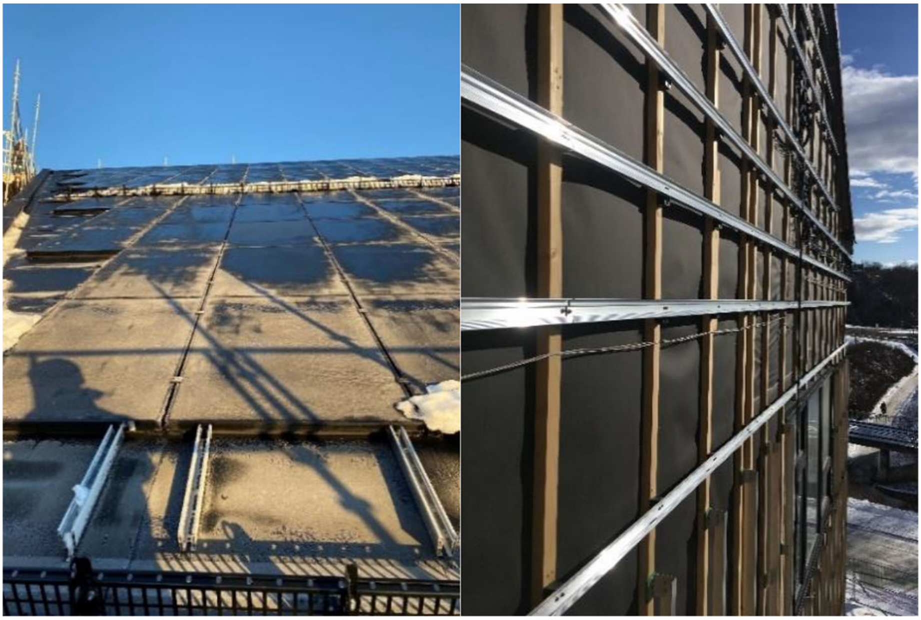

Figure 1. **The roof construction (left side) and wall construction (right side) behind the BIPV modules at the ZEB Laboratory [Source: SINTEF].**

All modules are tilted 10° towards east or west and follow the slope of the roof north and south. A total of 14 inverters are connected to the PV modules.

2.2.3. Structural Layout of Powerhouse Brattøra Powerhouse Brattøra is an office building in Trondheim, Norway [41]. The supporting documentation reviewed for Powerhouse Brattørkaia consist of three reports containing fire safety premises, verification of fire safety concept and fire safety assessment of deviations from NEK 400 [25], as well as fire test reports for the PV installation. The documentation was discussed with the fire consultant, a presentation of the planning and installation of the building was made by the building contractor and discussed in a reference group workshop, and on-site visits to the building site during construction and after completion were made. Information exchange with the local fire service was also conducted.

The building is designed to produce more energy than it consumes during its lifetime, aiming for the energy certification BREEAM Outstanding (Building Research Establishment Environmental Assessment Methodology [37]). The building was completed in 2019 and has a total area of 18 700 m^2 distributed over 9 floors, in addition to a parking cellar with base area of 9 997 m^2. BIPV systems are installed on parts of the south and west facades, totally 981 m^2 and BAPV systems are installed on nearly the entire roof area of 1886 m^2, see Fig. 3. The roof is tilted 19 degrees to the south and spans floor 3 to 9. The installed PV sys-

Figure 2. An overview of the PV installations located at Heimdal Upper Secondary School [Source: Trøndelag County Council].

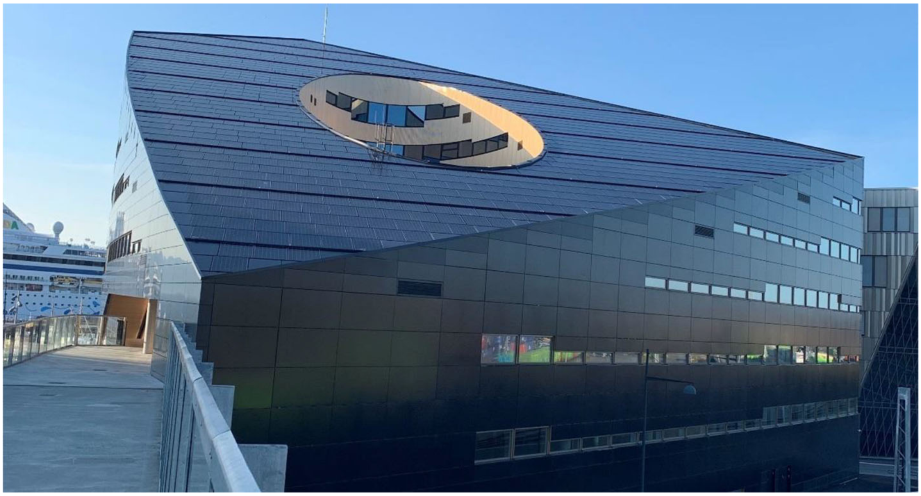

Figure 3. Powerhouse Brattøra after completion, showing parts of the south-facing façade in which parts of the façade is covered by BIPV modules and the roof with BAPV modules [Source: SINTEF].

tems have an expected total peak power up to 629 kW. The expected energy consumption of the building is 14.8 kWh/m^2 yearly. To compare, the Norwegian Building Regulation TEK17 [21] requires an energy consumption below 115 kWh/m^2 per year. The energy production from the PV system at the building is estimated to 485 000 kWh per year. A technical room designed for a battery energy storage system is prepared, but no system is currently installed.

The roof has a fire resistance of REI 90 in accordance to EN 13501–2 [38] and consists of, from the inside and out: gypsum boards, cross-laminated timber elements (CLT) [38], vapour barrier, 300 mm mineral wool insulation, two layers of asphalt roofing membrane with fire classification B_{ROOF} (t2) in accordance to EN 13501–5 [42] [42] on the specific construction, wooden battens and PV modules. There is a 150 mm ventilated air cavity between the PV modules and the underlaying roof construction. The PV modules are attached to the building through an aluminium railing system bolted to the underlying roof construction.

The façade areas covered with BIPV modules consist of an aluminium railing system with 140 mm air cavity between the modules and the underlying wall construction, which is a timber frame wall with stone wool insulation between the studs. The wall has vapour barrier and gypsum boards on the inside, and a wind barrier of gypsum board on the outside.

2.2.4. Structural Layout of Spar Snarøya Spar Snarøya is a grocery store in Bærum, Norway. The supporting documentation reviewed for the building was the fire safety strategy from the early stages of the project. Fire safety concept for the completed building was not available.

Spar Snarøya was completed in 2018 with 1 352 m^2 on one floor. The building has a green profile, with emphasis on using environmentally friendly materials, and many innovative solutions were chosen to reduce the energy consumption and CO_2 footprint. The structure is of timber, and the construction of external walls and roof are designed to reduce the required energy for heating and cooling. BIPV modules are mounted on the south and east façades as a ventilated cladding on an underlying construction of cross-laminated timber elements, see Fig. 4. The 100 m^2 of BIPV has an energy production of approximately 7,000 kWh per year. The PV panels are combined with wooden cladding. Neither documentation for the construction details of the PV installation nor the reaction to fire classification have been received.

External walls are constructed of two layers of cross-laminated timber elements without thermal insulation. Between the timber elements and the PV modules there is a vertical continuous ventilation cavity. There is no requirement for the external walls to function as fire separation as the distance to other buildings and fire compartments is large.

2.2.5. Structural Layout of KIWI Dalgård KIWI Dalgård is a grocery store in Trondheim, Norway. The supporting documentation reviewed for the building was the fire safety concept from the early stages of the project.

KIWI Dalgård was completed in 2017 and has a floor area of 1 250 m^2 on one level. The building has a green profile, with focus on environmentally friendly

Figure 4. Spar Snarøya after completion, showing two of the facades with BIPV modules [Source: Norgesgruppen AS].

Figure 5. KIWI Dalgård after completion, showing two of the facades with BIPV modules and the roof with BAPV modules [Source: KIWI Norge AS].

energy production. BIPV modules are installed on two facades and BAPV modules are installed on parts of the roof, see Fig. 5. A total of 560 m^2 PV panels produce aproximately 56 000 kWh of energy per year.The PV panels on the walls are installed as ventilated cladding with a ventilation cavity behind, and combined with wooden cladding. The roof is a traditional steel structure with steel trusses and corrugated steel panels. Details about the build-up of the roof and wall constructions are not obtained. Neither documentation for the construction details of the PV installation nor the reaction to fire classification have been received.

There is no requirement for the external walls to function as fire separation as the distance to other buildings and fire compartments is large.

3. Results

3.1. Findings From the Qualitative, Semi-Structured Interviews

The systematised and analysed results from the semi-structured interviews are summarised below, under the three main topics given in chapter 2.1. These findings are the interview objects' subjective opinions, and do not necessarily agree with the authors or other stakeholders' opinions. All informants shared their knowledge and experience on all the three main topics, even though not all informants had equal amounts of experience and information to share on the different topics and subtopics.

3.1.1. Measures to Reduce the Fire Risk of PV Installations The three consultants that were interviewed gave information about different technical and organisational measures they implement to reduce the fire risk. The consultants confirmed using the same fire safety measures as the Norwegian standard for electrical components and systems NEK 400 [25] denotes. They design the facilities as simple as possible, in terms of cables and components. Furthermore, they recommended to use components of the same type and brand throughout the whole PV system.

To reduce the risk of transient overvoltage and lightning, systems with transient overvoltage protection are usually designed on the DC side. However, the interviewees meant that in some cases this is not necessary from a holistic perspective of the facility and the building. Because electrical earthing is closely connected to the lightning conductor, different strategies for different buildings are usually considered.

The consulting electrical engineer informed that in most installations, turning off the power at the inverters is sufficient compared to using a shutdown switch. However, a shutdown switch is required in cases where it is difficult to install DC cables in a safely manner due to the layout of the building. It has not been evaluated in the current study whether installing shutdown switches is a widespread practise in Norway, but it was pointed out by the fire safety consultant as preferred and recommended, especially for projects of a certain size involving PV systems.

All three consultants considered DC power reducing components such as optimisers and microinverters to be unsafe because they include several components that can lead to malfunctions and potentially increase the risk of fire. They were also not considered a cost-effective solution as component costs increase.

The consulting electrical engineer emphasised the importance of multidisciplinary collaboration, for instance to ensure that cables are placed in cable racks and strapped to ensure that they will not impediment the work of the fire service during a fire situation. This is confirmed by one of the fire safety consultants who informed that all cables and power circuit breakers exposed to climatic stress are strapped together and marked before they are placed in cable racks. The locations of the cable trays are strictly planned in cooperation with the supplier to avoid blocking of the fire service's access to the roof construction beneath. The interviewees' experience is that the different disciplines collaborate to find the best solutions for service installation penetration seals through fire rated building parts.

The building contractor referred to a specific building where they had installed both BIPV and BAPV modules, in which the amount of electronics on the roof and façade was kept at a minimum to reduce the possibility of error sources in connection to the PV systems. Fire resistant cables were led through a railing system to ensure the integrity of electrical circuits for a certain time after a fire starts.

Thermography with drone was also mentioned as a possible safety measure, both directly after completion and with regular intervals in the following years. The purpose is to discover damaged cables and malfunctioning modules that can reduce the effectiveness of the system and be a potential fire risk. Outdoor infrared thermography of PV installations is covered in the technical specification IEC TS 62446–3:2017 [43].

Overall, the following safety measures have been identified in the interviews as the most important, some of them have already been implemented in existing building projects in Norway:

– Mechanisms to prevent ignition:

o Arcing fault detection systems
p Electrical earthing
q Lightning conductor with overvoltage protection
r Protection against short circuiting
s Using DC-connectors from the same manufacturer
t Thermography to detect overheating in cables and modules

– Shutdown of the PV system should in most cases be performed by turning off the inverter instead of using a dedicated shutdown switch.
– Micro inverters and power optimisers can reduce DC-voltage, but are not recommended measures because they include several components that can lead to malfunctions and potentially increase the risk of fire
– Protection of cables should be performed by using:

o Double isolated cables
p Fire resistant cables
q Planned location of cable racks through fire rated building parts
r Fire rated penetration seals
s Fire rated roof construction

3.1.2. Structural Aspects of the Building One of the fire safety consultants frequently utilizes international regulations like ASTM-standard E-108/UL 790 [44] and official European guidance documents. The specific guidelines were unfortunately not referenced. Research on fire in PV modules are according to the informants often used as a basis for design decisions. An example without reference was drawn by one informant, where results from a reviewed literature research had indicated that one of the frequent causes of fire is poor workmanship during installation of the modules. The designers chose to introduce third party control accompanied with a check list as a preventive action based on these research results. Another fire safety consultant reported that they primarily used the Norwegian regulations and guidelines, like NEK 400 [25] and a guidance document composed by a cluster of companies working with PV systems [45]. One of the fire consultants pointed out that regulations and guidelines still need further development to better take care of issues like fire spread and facilitation for the fire and rescue services, and that these issues should be addressed as part of the building and fire safety regulations, rather than as part of the electrical installation regulations.

One of the fire consultants interviewed informed that they usually specify the rear surface of the modules to be non-combustible independently of the underlying construction, i.e. stone wool is used behind the modules together with aluminium installation racks. In cases where the underlying construction is combustible, they recommend a 30 mm layer of incombustible insulation, usually stone wool, as a barrier between the PV modules and the underlying construction.

The building contractor gave information about a specific construction project involving BAPV modules on the roof and BIPV modules on the façade, in which fire safety considerations were made for several aspects of the building phases, including detailing. This building was designed with fire resistant, internal rain gutters in case of fire, to prevent melted polyester from the PV modules from entering the building. The internal rain gutters ended up in a technical room performed as a fire compartment.

Summarised, the interview objects recommended the following measures to reduce the risk of fire and spread of fire in the underlying construction:

- Use of third-party control after installation to uncover poor workmanship and faults in the cabling
- Use of non-combustible materials in the underlying construction, i.e. aluminium racks instead of wooden laths and a stone wool layer on top of combustible insulation

3.1.3. Arrangements for the Fire Service One of the fire safety consultants informed that they preferably do an on-site inspection together with the fire service when the PV installation is finalised. The purpose is familiarisation with the system and the possibility to make small changes to the design, to ensure safety and access for the fire service. On the other hand, the informant from the fire service expressed that the fire service in most cases were involved too late in the building process, and their ability to influence the design choices made for fire safety purposes were less.

According to the informant from the fire services, the fire service in larger cities have developed internal procedures and guidance documents that regulate the routines for firefighters entering a building equipped with PV modules. The first action is to get an overview of the system and its components. The informant from the fire service reports that fire safety plans are only prepared for large and complex buildings, not smaller or simpler buildings with PV installations, e.g. single family houses. It is important for the fire service to get sufficient information about access to and location of the PV installations, independently of the building's size and complexity. The informant emphasises that satisfactory location maps with a clear marking of the equipment and hose connection points in the building, together with clear marking of access to the roof, is considered essential.

In cases where the PV modules are blocking access to the roof construction or there are chances for involvement with current-carrying components, the fire service may, according to several informants, break the circuit in three different ways by switching off the inverter manually, using a shutdown switch to cut the DC-line between the PV modules and the inverter, or by breaking the circuit by disconnecting junctions on the panels, which result in the circuit no longer being a loop. The third option requires that each PV module is disconnected from the circuit and removed before the fire service can continue to open the roof construction for smoke venting purposes. If every panel has its own power switch, there will be no higher voltage than from one single panel, which is less than 50 V. This solution is considered very time consuming and requires a lot of effort. As a safety measure this work is performed as if the modules are still current-carrying, which includes keeping a safe distance. Safe distances are established in cases where water is used as an extinguishing medium; 1 m distance for scattered water jets and 5 m for compact water jets. Other manual extinguishing mediums like powder, foam and CO_2 are also considered safe for use and suitable for extinguishing small, local fires in the PV installation.

Buildings where PV modules are installed in retrospect are the most challenging according to the informant from the fire service, i.e. not new-builds such as the case buildings presented in this study. In these cases, the communication between the fire services and the module suppliers is often poor or lacking, and very little information is made available about the construction below the modules. The informant has also experienced PV installations that are not properly attached to the building below, i.e. strapped to the underlying construction instead of attached with proper fasteners. Other examples of poor arrangements for the fire service are lack of walkways between the modules.

Summarised, the most important arrangements for the fire service according to the informants are found to be:

- Early involvement of the fire service in design decisions is important to arrange safe and sufficient measures for the fire service, as well as a common on-site inspection after the PV installation is finalised
- sufficient information about access to and location of the PV installations, independently of the building's size and complexity

– location maps with a clear marking of the equipment and hose connection points in the building, together with clear marking of access to the roof, is considered essential

3.2. Qualitative Design Review of the Case Buildings

3.2.1. Fire Safety Design for ZEB Laboratory The ZEB Laboratory is classified in risk class 2 and fire class 2 according to the prescriptive guidelines developed for the Norwegian Building Regulations [22]. Due to the constructional flexibility requirements for the laboratory, the whole building is designed as one fire compartment except for some small technical rooms including the inverter room, and the escape staircase, which are separate fire compartments. An automatic sprinkler system and a full coverage fire detection and alarm system are installed in all rooms according to EN 12845 [46], NS 3960 [47]and EN 54 [48]. There are no fire or smoke detectors covering the PV-modules.

Several deviations from NEK 400 [25] have been made, all of them regarding the roof installations. According to the prescriptive electrotechnical norm, PV modules mounted on roofs without access from the inside must be installed with a distance of at least 1 m from one of the roof edges, preferably on the same side as the fire engine designated area. The objective of this requirement is to ensure sufficient physical space and access for fire extinguishing purposes. The fire safety consultant has chosen to deviate from this requirement on the following premises:

– Except for one escape stair and technical rooms, the building is designed as one big fire compartment which will be accessible via the north façade and through several entrances on the ground floor.
– The building is easily accessible from the north and there is a suitable designated area for the fire engine next to the building.
– There is good accessibility for the fire service around the building and good access to extinguishing water in immediate vicinity.
– The building height is considered low; 12 m to the top floor and 23 m to the roof top on north side. In addition, the total basal area is small, approximately 500 m^2. These factors make a fire situation more surveyable.

NEK 400 [25] requires that a walkway with at least one-meter clear width between the PV modules is established for every 40^{th} meter. As the roof at the ZEB Laboratory is shorter than 40 m in both directions, this requirement does not apply.

Another deviation performed in the fire design, not directly in connection with the PV modules, is a reduction in fire resistance on the rafter roof construction, i.e. the secondary loadbearing constructional elements, from R 60 to R 30. The roof construction is a rafter roof consisting of I-joists and non-combustible insulation, which are resting on glulam beams. The I-joists have a fire resistance of R 15, according to the supplier. The glulam beams have a fire resistance of R 60. The roofing membrane is specified in the fire safety concept to fulfil a fire classification $B_{ROOF}(t2)$ in accordance with EN 13501–5 [42] on the specific roof construction. The fire safety concept also clearly states that materials used in the air cavity between the PV modules and the roofing membrane must be non-combustible, i.e. with reaction to fire classification A2-s1,d0 in accordance to EN 13501–1 [49].

A shutdown switch for the PV modules is installed by the entrance of the building to enable possible disconnection of the modules from the power grid in the building. Orientation maps showing the location of the PV modules is also found by the entrance.

A meeting with the local fire service had been carried out during the design phase to establish a common understanding of the necessary extinguishing efforts in relation to the PV modules on the roof and façades. The following initiatives were proposed by the fire service:

- Cavities behind the PV modules must be performed with barriers to avoid fire spreading throughout the roof and facades covered by modules. Due to the limited size of the ZEB Laboratory the entire roof and each façade are separate areas which is considered to be sufficient barriers.
- Normally the fire service requires access to the roof for smoke venting purposes. Establishing smoke vents at the top of the north façade will ensure sufficient smoke ventilation without interference with the roof construction.
- To aim for a simple and easy attachment system for the roof mounted PV modules to avoid downfall.
- The use of non-combustible materials in the cavities behind the PV modules is a premise in the fire safety design concept that must be transferred from design phase to the building phase.

The PV modules on the façades and the wall construction behind them, see picture on the right side in Fig. 1, are in little extent referred to in the fire safety concept. There is only a general mentioning of the materials in the cavity behind the PV modules which must mainly consist of non-combustible materials, i.e. reaction to fire classification A2-s1,d0. The fire safety concept also states that if combustible insulation is considered used, this initiative must be clarified and planned in cooperation with the fire safety consultant and the person in charge of the PV installations.

3.2.2. Fire Safety Design for Heimdal Upper Secondary School The building contains areas with different activities with risk classes from 2 to 5, and fire class 3 according to the fire safety concept. An overview of the building in Fig. 2 shows the 11 different sections of PV modules, and their positions on the roof. A closer view of the PV modules is shown in Fig. 6. The central part of the building is an open atrium spanning over the three top floors with large glass sections in the ceiling. This part is not covered with PV modules and has reaction to fire classification A2-s1, d0, i.e. non-combustible in accordance to EN 13501–1 [49]. The roof construction is made with non-combustible insulation and the constructional elements have a fire resistance rating R 60 in accordance with EN 13501–2 [38]. The

Figure 6. BAPV modules mounted on the roof at Heimdal Upper Secondary School [Source: Trøndelag County Council].

roofing membrane has classification $B_{ROOF}(t2)$ in accordance with EN 13501–5 [42] on the specific construction. Vertical fire spread between fire cells is prevented by an internal automatic sprinkler system designed according to EN 12845 [46]. The fire safety requirements of the roof construction and sprinkler system in the fire safety concept are made without any reference to the PV-installation.

The inverters for the PV installations are located in a technical room on the roof with a direct path for cabling to the main switchboard room on the lower ground floor. Only AC-cabling is continued further into the building from the technical room on the roof. The fire service participated in a meeting with the fire safety consultants discussing the possibility for firefighting on the roof where they agreed to ensure easy access for fire extinguishing on the roof, including underneath the PV modules. Apart from these details, there is little information on the PV installation in the provided fire safety documentation. Since PV modules are only located on the roof, the fire safety measures for the facades have not taken the PV installations into account. There is also no DC-cabling present inside the building except for the technical room on top of the roof where the inverters are placed. The PV installation is not mentioned as a technical installation with described measures to prevent ignition or spread of fire.

According to the building owner, the company installing the PV modules was responsible for the electric installations of all the PV modules, including DC-cabling and inverters. This company is also contracted to perform service and maintenance of the PV installation. Connections and cabling from the inverters to the main switchboards were managed by the electrical contractor that had the responsibility for the other electric installations in the building.

3.2.3. Fire Safety Design for Powerhouse Brattøra The office area of Powerhouse Brattøra as shown in Fig. 3 is classified as risk class 2, and the cafeteria and café on the ground floor as risk class 5 as given in the guidance document pertaining the Norwegian Building Regulations [22].The whole building is categorised in fire class 3 in the same system. The fire resistance requirements of loadbearing structures and fire separating floors is R 90, performed in a non-combustible material with reaction to fire classification A2-s1,d0 in accordance to EN 13501–1 [49]. Powerhouse Brattøra, the two neighbouring buildings and their shared parking cellar are designed as one fire section in the Norwegian Building Regulation system [22]. Active fire protection measures installed include automatic sprinkler system and fire alarm system.

During the design and installation phase of the project, several measures were taken to reduce the probability of a fire starting in the PV systems, and to facilitate firefighting efforts from the fire service. These measures were made based on a collaboration between the building contractor and fire consultant, with input from the local fire and rescue service on all key challenges regarding the PV modules.

To reduce the probability of fire ignition in the PV installation, all plugs were fitted with appropriate tools by instructed personnel and all connection points were suspended at least 100 mm above the roofing membrane. The number of electrical components on the roof and façades are kept at a minimum to reduce the number of error sources in connection to the PV modules. Cables are led through an aluminium railing system. Inverters are located in technical rooms below the roof on the top floors to minimise the number of live DC cables inside the building. Originally, the planned inverter location was in a battery room in the basement or lower floors of the building. However, at the request of the fire consultant the inverter location was moved to the closest reasonable location to the roof, to avoid leading live cables through the building. A fire alarm and extinguishing system are installed in the technical rooms as fire safety measures. The relevant fire characteristics of the PV modules were tested in accordance with ANSI / UL 790 [50] and IEC 61730–2 [51] and were classified in accordance with ANSI / UL 1703 [52] as Class C.

In terms of fire safety design, a key fire safety measure was high fire resistance rating of the roof construction to prevent a fire on the roof from spreading to the inside of the building for 90 minutes, and to prevent a fire inside the building from breaking through the roof. The roof construction is therefore designed with a fire resistance rating of REI 90 in accordance to EN 13501–2 [38]. Other than the fire safety measures described above, there was little that distinguished this building from a normal office building, according to the fire consultant. Their conclusion was therefore that there was little need for further measures or studies for this building compared to other office buildings.

To facilitate efforts by the fire service, the different areas of BAPV on the roof are separated with a steel-gridded walkway of 200 mm width. Secured walkways were made at every fifth row of PV modules, as well as at the cornice. The walkways also function as snow and ice barriers and facilitate ventilation of the PV modules. In the event of a fire alarm, inverters are switched off automatically, which means that the AC and DC circuits are broken, and only DC cables are live due to voltage generated by the PV modules. This voltage may still be high enough to pose a danger of current passage when touched.

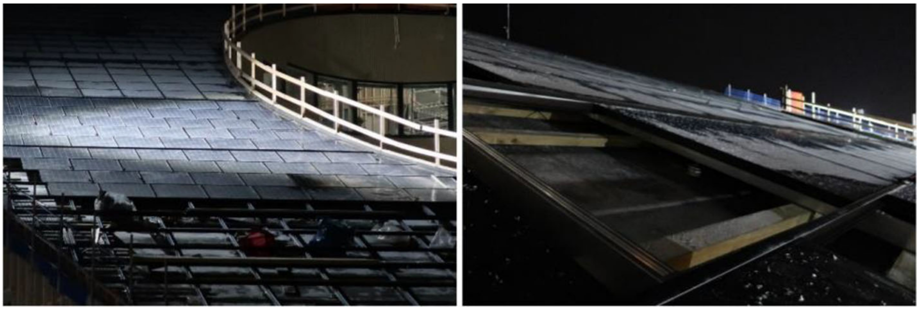

Figure 7. Details from the mounting of PV modules on the roof of Powerhouse, with asphalt roofing membrane, ventilated air gap, wood battens, aluminium attachment system and PV modules [Source: RISE Fire Research AS].

The BAPV modules on the roof as shown in Fig. 7 are designed for tool-less removing, which imply that the modules may be lifted off without the use of tools, for example by the fire and rescue service in the case of a fire. A wire keeps the modules from being forced out of position by wind forces. The electrical cables on these modules are clipped on, and the contact will disconnect in case of removal. According to the contractor, the modules are without risk of electric shock in case of contact. The BIPV façade modules are more difficult to remove. The weight is 70 kg per module, and the modules must be dismounted starting from the top of the building and moving downwards. As part of the engineering process of the building, the fire service has, however, added that even with modules that are easily dismantled and have low-weight, removal during extinguishing efforts would not be an easy task due to the many other factors playing a role during the chaotic situation of a fire event. The local fire service was invited to inspect the building after completion to get acquainted with cabling, the cabling route including a cable bridge, the location of inverters and signage in the building.

A yearly inspection with a drone with thermographic camera is implemented as part of the buildings' management, operation and maintenance routines, to mitigate potential fire risks.

3.2.4. Fire Safety Design for Spar Snarøya The public grocery store area of Spar Snarøya is classified as risk class 5, while the staff room, storage and technical room are in risk class 2. The building is placed in fire class 1 because it only has one storey [22]. The fire resistance requirements of loadbearing walls is R 15 and R 30, and the external surfaces must meet reaction to fire class D-s3,d0 or better, in accordance to EN 13501–2 [38] and EN 13501–1 [48]. Active fire protection measures installed include a fire alarm system.

The BIPV installation is not mentioned in the fire safety strategy document and might have been added to the project at a later stage, e.g., in the detailing or construction stage.

The building is designed before the 2018-version of NEK 400 was implemented, and a design for the PV installations that include fire safety measures was not obtained. It is assumed that this is because fire safety was not evaluated.

3.2.5. Fire Safety Design for KIWI Dalgård The grocery store KIWI Dalgård is placed in risk class 5 and fire class 1, as it only has one storey. The fire resistance requirements for the loadbearing structure is R 15, and the external surfaces must meet reaction to fire class D-s3,d0 or better, in accordance to EN 13501–2 [38] and EN 13501–1 [48].The roofing must have class B_{ROOF}(t2) in accordance with EN 13501–5 [42]. A fire alarm system is installed in the building.

The fire safety concept does not mention the BIPV and BAPV installations, and the installations might also for this building have been included at a later stage, as for Spar Snarøya, see pt. 3.2.4.

KIWI Dalgård was designed before 2018 and therefore not according to the new version of NEK 400. The fire safety concept does not include evaluations of the PV installations, and documentation of fire safety measures related to the installations were not available.

4. Discussion

Factors affecting the fire safety design of photovoltaic installations under performance-based building regulations in Norway have been studied. Measures to reduce the fire risk, structural aspects related to the fire safety, and arrangements for the fire services were discussed in the interviews. Fire safety measures related to the PV system implemented on newbuilt buildings were studied through the case buildings. Details about the case buildings are given in Table 2.

The study is limited to five case buildings, and a handful of interview objects, and should therefore be viewed as indicative. Including more case buildings and a larger group of stakeholders in interviews, or other forms of qualitative surveys could have given a broader view and more information on the topic and is encouraged for future work.

The results show that the main factors affecting the fire safety design are (1) whether the building is a pioneering building, (2) whether the prescriptive norm NEK 400 was used as a basis for design, (3) the level of knowledge and experience of the fire safety engineer, and (4) whether the PV system is integrated (BIPV) or applied (BAPV). These four factors are scrutinised below.

In general, important and relevant measures to ensure the required fire safety level for the buildings are to prevent arcing, sufficient actions to cut of the power supply in case of fire, reduction of DC voltage, cable protection, limit the amount of combustible materials behind the PV modules and in the underlying construction and fire rated roof construction to prevent fire spreading from PV modules to the inside of the building and vice versa. Additionally, good communication and cooperation with the fire service throughout the whole design and building process is also emphasised in the interviews to ease extinguishing work in case of a fire involving PV modules.

Table 2
Details About the Case Buildings Studied in this Article

Case building	ZEB LAB (2020)		
Building category	Office building	Risk / Fire class	2/2
Type of PV	BIPV	Location	Roof, all facades
Number of modules	701	Area size	963 m^2
Classification of PV	–	Standards used	NEK 400 with deviations
Fire resistance rating roof/wall	Main load-bearing structure: R 60 Secondary load-bearing structure: R 30		
Construction	Roof: PV modules with ventilated cavity behind, timber battens, roofing, timber beams and mineral wool insulation. Facades: Ventilated PV modules, timber and metal battens, timber frame structure, mineral wool insulation		
Fire safety measures	Sprinkler system, full coverage fire detection and alarm system in all rooms, EN 12,845, NS 3960, EN 54. Nothing on the roof or facades		
Access for fire services	–		
Case building	Heimdal Upper Secondary school (2018)		
Building category	School	Risk / Fire class	
Type of PV	BAPV	Location	Roof
Number of modules	1200	Area size	1937 m^2
Classification of PV	–	Standards used	
Fire resistance rating roof/wall	Main load-bearing structure: R 60		
Construction	Load-bearing elements of steel profiles, plywood boards and mineral wool insulation		
Fire safety measures	Sprinkler system inside the building, EN 12,845. Only AC-cabling from the PV is continued into the building from the roof		
Access for fire services	Easy access for fire extinguishing on the roof		
Case building	Powerhouse Brattøra (2019)		
Building category	Office building	Risk/Fire class	2&5/3
Type of PV	Roof: BAPV Facades: BIPV	Location	Roof, 2 facades
Number of modules		Area size	Roof: 1886 m^2 Facades: 981 m^2
Classification of PV	Class C, ANSI/UL 1703	Standards used	NEK 400 with deviations
Fire resistance rating roof/wall	Roof: REI 90. Walls: No requirement because they are infill walls and not load-bearing		

Table 2
continued

Construction	Roof: Cross-laminated timber elements, mineral wool insulation, roofing, wooden battens. Facades: Ventilated PV modules, aluminium battens, timber frame structure, mineral wool insulation		
Fire safety measures	Sprinkler system and fire alarm system inside the building. All connection points suspended ≥ 100 mm above roofing. Minimum number of electrical components on roof and façades Cables led through aluminium railing system. Minimised number of live DC cables inside the building. Annual inspection with thermographic camera		
Access for fire services	AC and DC circuits are broken in case of fire alarm. Easy access under PV modules on roof. Steel-gridded walkway on roof along cornice and between PV modules		
Case building	Spar Snarøya (2018)		
Building category	Grocery store	Risk / Fire class	1&5 / 1
Type of PV	Facades: BIPV	Location	2 facades
Number of modules		Area size	100 m^2
Classification of PV	Unknown	Standards used	
Fire resistance rating roof/wall	R 15/30 for load-bearing system. No requirements for fire separation in external walls		
Construction	Facades: Ventilated PV modules, battens of unknown material, cross-laminated timber elements		
Fire safety measures	Fire alarm system inside the building		
Access for fire services	Unknown		
Case building	KIWI Dalgård (2017)		
Building category	Grocery store	Risk / Fire class	5/1
Type of PV	Roof: BAPV Facades: BIPV	Location	Roof, 2 facades
Number of modules		Area size	Totally: 560 m^2
Classification of PV		Standards used	
Fire resistance rating roof/wall	R 15 for load-bearing system. No requirements for fire separation in external walls		
Construction	Roof: Corrugated steel panels, insulation, roofing, battens. Facades: Ventilated PV modules on ventilated cavity, unknown construction behind		
Fire safety measures	Fire alarm system inside the building		
Access for fire services	Unknown		

4.1. Pioneering Buildings

Two of the case buildings in this study, ZEB Laboratory and Powerhouse Brattøra, are considered pioneering buildings, i.e., first of its kind as defined in Sect. "4". The design review of these buildings indicates that the detailing level in fire safety design regarding the PV system depends on this factor. These buildings have a larger budget and time frame to develop innovative solutions, and can therefore address the challenges in detail.

Contrary to the pioneering buildings, the BIPV installations on Spar Snarøya and KIWI Dalgård are not mentioned in the fire safety strategy documents for the buildings.PV installations on these buildings have probably been added to the project at a later stage, e.g., in the detailing or construction stage. Or the fire safety engineer might have assumed that the fire safety of the PV installations would be addressed by the electrotechnical design for the building, or the supplier of the PV installations. It is therefore assumed that the fire safety for the building is not dealt with in a holistic approach where also the PV installations are considered.

In all buildings there are many measures to ensure the fire safety, and they are connected to each other. However, in this study the focus is only on the fire safety measures directly associated with the PV systems, i.e. solutions that are incorporated in the PV system or directly related to it.

4.2. Implementation of the NEK 400 Prescriptive Norm

The delicate balance between performance-based regulations and more prescriptive solutions has been found to be especially relevant for the use of the electrotechnical norm NEK 400 [25], which is prescriptive and central for electrical low voltage installations in Norway. This collection of standards contains normative requirements and the revision performed in 2018 was the first version including detailed information on PV installations on buildings. Yet, the latest version of NEK 400 does not cover all aspects related to the building, e.g., facilitation for the fire service, choice of construction materials and fire spread from the outside of the building and inwards. For four of the case buildings used in this article, Heimdal Upper Secondary School, Powerhouse Brattøra, Spar Snarøya and Kiwi Dalgård, the design phase was completed before 2018, hence this regulation had not come to operation. Based on the detailing level of the fire safety concepts and findings from the interviews, it seems that fire safety design of PV installations before the 2018-version was performed with larger variations and to a large extent based on the fire safety consultants' experience. With the more detailed prescriptive information given in the 2018-version, a more unified approach is seen in the case building ZEB Laboratory, but perhaps with less reliance on specialist knowledge, a trend also observed by Lange et al. [16]. The ZEB Laboratory is designed based on the 2018-version of NEK 400 and comprises a fire safety assessment of deviations from NEK 400. The arguments for these deviations are based on the importance of maximum energy production, which was prioritised at the expense of the fire services access to the roof.

4.3. The knowledge and Experience of Fire Safety Engineers

The fire risks and fire safety measures evaluated and implemented varies for the case buildings, where for some buildings (Powerhouse Brattøra) the fire safety design includes detailed evaluations of the fire risks and necessary measures, while for others the PV installations are not even mentioned in the fire safety concept (Spar Snarøya, KIWI Dalgård). The consultants use different background documents; FEL and NEK, ASTM, and various available research publications. In some cases, the use of non-combustible materials behind the PV is described, where for others, the material and construction behind is not considered. In Powerhouse Brattøra and ZEB Laboratory the roofs function as fire separation, but not the walls. And for Spar and KIWI there are no evaluations of the need for fire separation between the PV installations and the inside of the building. This indicates that the designers have varied knowledge, experience and background. Building regulations in Norway are performance-based, and there are no prescriptive solutions for how to achieve the required fire safety of PV installations. A guideline on how to evaluate the risks is also lacking. This requires that the fire safety engineers have the resources and ability to gather knowledge from available research, identify the risks, and develop effective measures to limit the probability and consequences of a fire involving the PV system. Fire safety engineers in Norway have various background, as there are no formal requirements. As described above, the fire safety design therefore varies. Central approval from the building authorities is not required for designers of PV installations, and consequently there is no formal required level of expertise. The responsibility must therefore be agreed upon in each building project.

When the fire safety concept does not include evaluations and measures for the fire safety, this is either not considered at all for the building, or someone else with knowledge and experience outside the fire safety field has made some evaluations. In some of the buildings this was performed by the suppliers of the PV installations. One can ask if they have the necessary competency to do a holistic fire safety design, taking into consideration the building constructions, all fire safety measures in the building, and the additional fire risks imposed by the PV installations.

As presented in the introduction, three key prevalent challenges were found in the literature related to fire safety aspects of PV installations on buildings: (1) the change in fire dynamics when introducing a PV module to a building envelope; with a potentially faster spread of flames and higher temperature in the gap between module and underlying surface [30, 31], (2) the lack of international harmonisation of existing test standards and the lack of test standards for documentation of fire safety on a system level, particularly regarding BIPV [32, 33], and (3) insufficient knowledge and experience amongst fire safety consultants [3]. The first two issues need to be addressed by the fire safety engineer during the design process, and would require an adequate education, knowledge level and experience in designing buildings according to performance-based regulations described as issue number three. The large number of PV incidents and the causing factors identified suggests that more knowledge about fire safety design of PV installations on buildings is crucial to enable a robust design of fire safe buildings with PV installations.

Only a few research studies were found on the fire properties and fire risks of PV installations [3–5]. The large number of PV fire incidents and the causing factors identified [6, 7] suggest that more knowledge about the fire risk of PV installations on buildings is crucial to enable fire safety engineers to perform proper fire safety design of PV installations. Prescriptive rules are easier to implement in the design but are not given for PV systems on buildings in the Norwegian building regulations. Fire safety design must therefore be based on the performance-based rules, requiring a higher level of knowledge and expertise amongst the engineers performing the fire safety design. Education of more fire safety engineers in methods for performance-based design is therefore needed. Less than 30 fire safety engineers are educated in Norway each year [53]. Therefore, it can be assumed that many of the consultants performing fire safety design of buildings do not have a formal background within this profession. The findings support this assumption, as there is a considerable spread and diversity in the fire safety measures considered, proposed and implemented in the buildings. It is also indicated by the differences in use of design tools, like research literature, as a foundation for fire safety measures. A recent study by Lange et.al. [16] show similar results also in other countries around the world. They argue that the lack of a well-defined accreditation framework for fire safety consultants poses challenges for the profession, with ethical challenges attached to the way the profession operates. Lange et al. also suggest that heavy reliance on prescriptive solutions opens for practitioners with little specialist knowledge. This challenge is not only relevant for fire safety design for PV installations, but since PVs are relatively new, guidelines and regulations related to fire design are still being developed.

4.4. PV System Integrated (BIPV) or Applied (BAPV): Measures to Reduce the Fire Risk of PV Installations

The degree of integration to the building also seems to affect the detailing level of the fire safety design; with more focus on details related to fire safety of BIPV compared with BAPV. This is probably caused by the lack of common regulations for BIPV and BAPV in Norway, and the absence of a guideline. It might also be due to the additional functions of the BIPV as they also need to be durable to weather exposure, watertight and provide fire protection. BAPV might be considered as a technical installation outside the building, and therefore not included in the fire safety analysis and fire design for the building. It falls within FEL and NEK 400 [24, 25], and this regulation does not require a fire risk analysis or documentation of the fire properties. While BIPV are considered as building products, for which the fire safety must be documented according to TEK17 [21] in addition to meeting requirements in FEL.

Installation of PV systems are regulated by FEL [24]. Assembly and installation of PV systems is a specialist area which spans across building technical and electrotechnical competence, but where smaller work tasks like connection of PV panels and preparing of DC cables can be performed by persons without any formal competence within electrotechnical or building technical areas [45]. In many cases the supplier of the PV system is also responsible for the design and installation of the PV system. When the supplier is strongly involved in the fire design related to the PV installation, the safety and reliability of the PV installation is hence strongly dependent on the competence of the supplier.

The need for specialist knowledge is also highly relevant because of the complexity of the PV systems and the need for a holistic understanding of the fire risks and safety measures. The fire resistance for the roof or wall construction is often considered necessary only to prevent fire spread from the inside of the building to the roof and wall. Findings from the case buildings and information from the interviews implies that several buildings are designed with a fire-resistant roof construction separating the PV installations from the remaining building. For the materials on the outside of the construction, it is common to only evaluate the reaction-to-fire properties, and not necessarily all the materials are considered. Requirements for the roof covering material are usually given in the fire safety concept, but other materials present in the cavity between the PV module and the substrate (e.g. wood laths, wirings and electrical connections, plastic frames and plastic attachments) are not considered. This situation has also been identified in the case buildings. The PV modules are tested with respect to external fire exposure, e.g. flying brands that land on top of the PV modules, but not with respect to a fire in the cavity. It has been demonstrated that fires in the cavities behind the PV modules affects the fire spread in terms of higher temperatures and faster spread of fire [30, 31]. These studies do not include combustible materials in the cavity, which is expected to give an even more severe fire and cause more extensive fire spread in the cavity due to the increased fire load.

The fire detection systems in all the case buildings are only located inside the building. The potential of a fire starting in or near the PV installations is not considered in the development of the fire safety concept, or it is not found to be necessary to install fire detection systems in relation to the PV systems. A fire can therefore develop undetected between the PV modules and the underlying construction and spread to large areas of the roof. Because the construction is usually built with fire resistance only from the inside, the fire can spread into the building within the required fire resistance period.

4.5. Arrangements for the Fire Service

Another finding from both interviews and case buildings is that the fire and rescue service is almost solely included in the design phase, but when the building process is completed the input from the fire service have often yielded for other purposes like energy harvesting optimisation. In Norway, the fire service only serves as an advisory part without any legal power of influence. Consequently, the chosen solutions are not always beneficial for extinguishing and rescue operations. A good cooperation between the fire and rescue service and the project team, as well as with the building owner during the end-use phase of the building is recommended. During the design phase, involvement should be done as early as possible when the degree of influence is highest.

4.6. Lack of Test Methods

Many test methods and standards related to PV systems are available in Europe according to the UK Building Research Establishment BRE [32] and RISE Fire Research [54]. In Europe, roof mounted BIPV or BAPV systems where the modules are considered a functional part of the roof, must be tested as a roofing product with respect to fire, i.e. tested according to TS 1187 [55] and classified in accordance to EN 13501–5 [42]. The construction layers immediately under the modules are included in this test and is a condition for the classification. BAPV systems are not defined as part of the roof construction and are therefore not covered by test and classification standards for roofing. The reaction-to-fire properties of BIPV systems on walls can be tested and classified according to EN 13501–1 [49], which includes the ventilated cavity and first layer in the construction behind. However, most of the test methods available do not consider the underlying construction. Information retrieved from the interviews and case buildings revealed that stakeholders have issues finding suitable test standards to document the fire risk and properties of PV installations, and sometimes test standards that are not developed for PV installations are used due to the lack of alternatives. According to Pester [32] and Mikalsen et.al. [54], the existing standards for PV installations are not harmonised. This means that the products do not need to be tested and certified according to the European Construction Products Regulative (CPR) [56], but on the other hand—achieving CE-marking for free trade in EU/EEU is a more complex and expensive procedure. In addition, there are no suitable test standards for documentation of the fire safety of the entire PV systems [32, 33].

In this study, many challenges related to fire safety in PV installations and suggestions for mitigating the risks are presented. Measures to limit the probability of ignition, limit the spread of fire and to facilitate the work of the fire brigade will all limit the overall potential fire risk. Having the risk situation today and the impact of suggested measures quantified would be beneficial for e.g. building owners and decision makers, but this would require further studies and improved, more uniform and detailed statistical data globally.

Solar energy has gained a strong focus since it currently is the only sustainable and renewable energy resource technology that can be applied to a building, to achieve sufficiently high energy production for classifications as a climate adapted building. The rapid development in the market is not necessarily followed as quickly by updated guidelines, regulations and formal distribution of responsibility. The result of this is that PV installations are handled by different disciplines during the design phase but with no discipline bearing the main responsibility for the interface between the electrical installation and the building construction.

5. Conclusions

The present study has investigated the factors affecting the fire safety design of PV installations on buildings in Norway under performance-based building regulations. The study has focused on how performance-based regulations in combination with a lack of guidelines and standards affects the overall fire safety considerations for PV installations, and therefore also the fire safety measures chosen. Both Building Applied PV and Building Integrated PV systems are considered.

Semi-structured interviews were carried out as an initial action to map how fire safety design with respect to PV installations are handled by different stakeholders during the building process. Investigations of the fire safety design of three case buildings were used to highlight differences in the design and practical solutions chosen for buildings and what factors influence the design choices made.

The results show that there are large variations in the fire safety designs and implementation of fire safety measures related to the PV installations. This is largely due to the lack of knowledge on the fire risks and necessary fire safety measure for PV installations, the degree of knowledge and experience of fire safety engineers developing the fire safety concepts, lack of relevant test standards to document the fire safety of modules, and lack of standard test methods to study the fire performance of the entire PV systems.

The main factors that are found to affect to which extent PV installations receives the required attention in the fire safety design phase are:

1) Whether the building was first of its kind as a pioneering building
2) Whether the building was built before or after the implementation of the detailed guidance specifically for PV installation added in 2018 to the national electrotechnical norm NEK 400.
3) The level of knowledge and experience of the fire safety consultant. This determines to which extent performance-based engineering tools are implemented. There is a large variation in the level of detailing in the design and installation phases.
4) The degree of integration of the PV system in the building (BAPV or BIPV). Building Integrated PV seems to receive a higher focus on fire safety. This is also linked to point 1).

It is how the regulations are interpreted and applied when there are no pre-accepted solutions available that affects the degree of integration in design and implementation, rather than the performance-based regulations themselves. This in turn depends on the level of knowledge and experience the fire safety consultant possesses. If professionals working with fire safety design do not possess the sufficient theoretical background to perform the fire safety analysis a performance-based legislation requires, the overall fire safety may be diminished.

An increased focus on the fire safety design related to PV installations is required, for all relevant stakeholders. This should be initiated by the industry and supported by authorities and research. An emphasis on developing relevant test standards and guidelines will enable a wider market uptake of PV installations, while still maintaining an adequate and unified fire safety level.

The stakeholders that were interviewed and the case buildings are Norwegian, however the results can also be relevant for countries with similar building regulations.

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Declarations

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

References

1. The European Parliament and the Council of the European Union, "Directive 2010/31/EU of the European Parliament and the Council of 19 May 2010 on the energy performance of buildings," European Union, 2010. Available: https://data.europa.eu/eli/dir/2010/31/oj
2. Jelle BP (2016) Building integrated photovoltaics: a concise description of the current state of the art and possible research pathways. Energies 9(21):1–30
3. Mazziotti L, Cancelliere P, Paduano G, Setti P, Sassi S (2016) Fire risk related to the use of PV systems in building facades. EDP Sciences 46:1–9
4. Laukamp et al, (2013) PV Fire Hazard—Analysis and Assessment of Fire Incidents. 28th European Photovoltaic Solar Energy Conference and Exhibition, pp. 4304–4311. https://doi.org/10.4229/28thEUPVSEC2013-5BV.7.71
5. Fiorentini L, Marmo L, Danzi E, Puccia V (2016) Fire risk assessment of photovoltaic plants. A case study moving from two large fires: from accident investigation and forensic engineering to fire risk assessment for reconstruction and permitting purposes. Chem Eng Trans 48:427–432
6. Cancelliere P (2016) PV electrical plants fire risk assessment and mitigation according to the Italian national fire services guidelines. Fire Mater 40(3):355–367
7. Mohd Nizam Ong N, Sadiq MA, Md Said MS, Jomaas G, Mohd Tohir MZ, Kristensen JS (2021) Fault tree analysis of fires on rooftops with photovoltaic systems. J Build Eng 46(13):103752
8. Aram M, Zhang X, Qi D, Ko Y (2021) A state-of-the-art review of fire safety of photovoltaic systems in buildings. J Clean Prod 308:127239
9. Pandian A, Bansal K, Thiruvadigal DJ, Sakthivel S (2016) Fire hazards and overheating caused by shading faults on photo voltaic solar pane. Fire Technol 52:349–364
10. Chow CL, Han SS, Ni XM (2016) A study on fire behaviour of combustible components of two commonly used photovoltaic panels. Fire Mater 41(1):65–83
11. P. Cancelliere, G. Manzini, G. Trania and M. G. Cavriani, "PV modules on buildings—Outlines of PV roof samples fire rating assessment," Fire Safety Journal, vol. 120, no. SI: Fire Safety Science: Proceedings of the 13th International Symposium, 2021
12. B. J. Meacham, "Performance-Based Building Regulatory Systems. Principles and Experiences.," Inter-jurisdiction Regulatory Collaboration Committee (IRCC), 2010
13. Hurley MJ, Rosenbaum ER (2015) Performance-based Fire Safety Design. CRC Press, Boca Raton
14. Östman B, Brandon D, Frantzich H (2017) Fire safety engineering in timber buildings. Fire Saf J 91:11–20
15. Fleischmann CM (2011) Is prescription the future of performance-based design?. Fire Saf Sci 10:77–94
16. Lange D, Torero JL, Osorio A, Lobel N, Maluk C, Hidalgo JP, Johnson P, Foley M, Brinson A (2021) Identifying the attributes of a profession in the practice and regulation of fire safety engineering. Fire Saf J 121:103274
17. Lange D, Torero J, Spinardi G, Law A, Johnson P, Brinson A, Maluk C, Hidalgo JP, Woodrow M (2022) A competency framework for fire safety engineering. Fire Safe J 122:103511
18. Bjelland H, Njå O (2022) A Nordic approach to fire safety engineering - Will standardization of probabilistic methods to verify dire safety designs of novel buildings improve engineering practices?. Saf Sci 148:105651
19. Direktoratet for Byggkvalitet (DiBK), "Temaveiledninger. Tilsyn. Vedlegg 3.2 Prosjekteringsprosessen. 3.2.3. Funksjonsbasert regelverk," Direktoratet for Byggkvalitet, 11 11

2012. [Online]. Available: https://dibk.no/saksbehandling/kommunalt-tilsyn/temaveiledninger/tilsyn/del-3–vedlegg/vedlegg-3.2/3.2.3.-funksjonsbasert/. [Accessed 06 09 2022]
20. V. Stenstad and W. Bjørkmann, "Performance-based Design in Norway - Room for improvement based on 10 years of experience," in 7th International Conference on Performance-based Codes and Fire Safety Design Methods, New Zealand, 2008
21. Ministry of Local Government and Regional Development, "FOR-2017–06–19–840. Forskrift om tekniske krav til byggverk (Byggteknisk forskrift)," Direktoratet for Byggkvalitet, 01 07 2017. [Online]. Available: https://lovdata.no/dokument/SF/forskrift/2017-06-19-840. [Accessed 06 09 2022]
22. Direktoratet for byggkvalitet (DiBK) (2017) Veiledning om tekniske krav til byggverk byggteknisk forskrift. Direktoratet for byggkvalitet, Oslo
23. International Energy Agency , "PVPS Snapshot of Global PV Markets. Report IEA-PVPS-T1–42:2022," International Energy Agency, 2022
24. Ministry of Justice and Public Security (1999) FOR-1998-11-06-1060. Forskrift om elektriske lavspenningsanlegg. Lovdata, Oslo
25. Norsk Elektroteknisk Komité (NEK), "NEK 400:2022 Electrical low voltage installations," Norsk Elektroteknisk Komite (NEK), 2022
26. Norge S (2015) NS 3510:2015. Safety glass in construction works. Requirements for design and classes in various application areas. Standard Norge, Oslo
27. T. Røsdal and F. Ørstavik, "Kommunikasjon i byggeprosjekter. Rapport 25/2011," Nordisk institutt for studier av innovasjon, forskning og utdanning, Oslo, 2011
28. Ontario Association of Fire Chiefs and the Canadian Solar Industries Association, "cansia.ca," 2015. [Online]. Available: https://www.cansia.ca/uploads/7/2/5/1/72513707/solar_electricity_safety_handbook_for_firefighters_.pdf. [Accessed 13 09 2022]
29. Mohd Nizam Ong NAF, Mohd Tohir MZ, Md Said MS, Shakir Nasif M, Hizami Alias A, Ramali M (2022) Development of fire safety best practices for rooftops grid-connected photovoltaic (PV) systems installation using systematic review methodology. Sustain Cities Soc 78:103637
30. Kristensen JS, Jomaas G (2018) Experimental study of the fire behaviour on Flat Roof constructions with multiple photovoltaic (PV) panels. Fire Technol 54:1807–1828
31. Kristensen JS, Faudzi FBM, Jomaas G (2021) Experimental study of flame spread underneath photovoltaic (PV) modules. Fire Safe J 120:103027
32. S. Pester and S. Woodman, "Fire and Solar PV Systems - Literature Review," BRE National Solar Centre, St Blazey, 2017
33. R. F. Mikalsen, A. S. Bøe, K. Glansberg, C. Sesseng, K. Storesund, R. Stølen and A. W. Brandt, "Energieffektive bygg og brannsikkerhet (RISE report no. 2019:02)," RISE Fire Research AS, Trondheim, 2019
34. Adams WC (2015) Conducting semi-structured interviews. Handbook of practical program evaluation Wiley, Newdelhi
35. Norwegian Green Building Council, "Byggalliansen.no," Norwegian Green Building Alliance, 14 04 2023. [Online]. Available: https://byggalliansen.no/sertifisering/om-breeam/manual-verktoy-og-hjelp/breeam-nor-faq/. [Accessed 14 04 2023]
36. SINTEF and NTNU, "ZEB Office Living Laboratory," SINTEF and NTNU, 2022. [Online]. Available: https://zeblab.no/. [Accessed 07 09 2022]
37. Fufa SM, Schlanbusch RD, Sørnes K, Inman M, Andresen I (2016) A norwegian ZEB definition guideline. ZEB project report 29–2016. SINTEF Academic Press, Trondheim
38. Norge S (2016) EN 13501–2:2016. Fire classification of construction products and building elements. Part 2: Classification using data from fire resistance tests, excluding ventilation services. Standard Norge, Oslo

39. Trøndelag Fylkeskommune, ''Heimdal videregående skole - Nyskolen står klar,'' Trøndelag Fylkeskommune, 15 08 2018. [Online]. Available: https://www.trondelagfylke.no/om-oss/eiendom/nyhetsarkiv/nyskolen-star-klar/. [Accessed 07 09 2022]
40. Schlanbusch RD, Fufa SM, Andresen I, Wigenstad T, Mjønes T (2017) ZEB pilot Heimdal high school and sports hall. Design phase report. ZEB Project Report 34–2017. SINTEF Academic Press, Trondheim
41. Powerhouse, ''Powerhouse Brattørkaia,'' Powerhouse, 2018. [Online]. Available: https://www.powerhouse.no/prosjekter/brattorkaia/. [Accessed 07 09 2022]
42. Norge S (2016) EN 13501–5:2016. Fire classification of construction products and building elements. Part 5: Classification using data from external fire exposure to roof tests. Standard Norge, Oslo
43. *Photovoltaic (PV) Systems - Requirements for testing, documentation and maintenance - Part 3: Photovoltaic modules and plants - Outdoor infrared thermography,* NEK IEC TS 62446-3:2017, Standard Norge, Oslo, 2017
44. *Standard test methods for fire tests of roof coverings*, ASTM E108:20a, ASTM International, 2020
45. Norsk Solenergiforening og Solenergiklyngen, ''Praksisbeskrivelse: Organisering og gjennomføring av installasjon av solcelleanlegg,'' 04 2019. [Online]. Available: https://www.solenergi.no/rapporter. [Accessed 27 09 2022]
46. Norge S (2015) EN 12845:2015 + A1:2019. Fixed firefighting systems. Automatic sprinkler systems. Design, installation and maintenance. Standard Norge, Oslo
47. Norge S (2019) NS 3960:2019 Fire detection and alarm systems. Design, installation, operation and maintenance. Standard Norge, Oslo
48. Norge S (2019) EN 54–3:2014 + A1:2019. Brannalarmanlegg - Del 3: Brannalarmutstyr - akustisk alarmorgan. Standard Norge, Oslo
49. Norge S (2018) EN 13501–1:2018. Fire classification of construction products and building elements. Part 1: Classification using data from reaction to fire tests. Standard Norge, Oslo
50. *Standard for Standard Test Methods for Fire Tests of Roof Coverings*, ANSI/UL 790-2022, UL Standards, 2022
51. Norsk Elektroteknisk Komité (NEK) (2018) EN IEC 61730–2:2018 Photovoltaic (PV) module safety qualification. Part 2: Requirements for testing. NEK, Oslo
52. *Standard for Flat-Plate Photovoltaic Modules and Panels*, ANSI/UL 1703-2018, UL Standards, 2018
53. Teknisk Ukeblad, ''Mange jobber venter på ingeniører som gløder for brannvern - men få vil studere,'' Teknisk Ukeblad, 11 04 2021. [Online]. Available: https://www.tu.no/artikler/mange-jobber-venter-pa-ingeniorer-som-gloder-for-brannvern-men-fa-vil-studere/508949. [Accessed 26 09 2022]
54. Stølen R, MIkalsen RF, Stensaas JP (2018) Solcelleteknologi og brannsikkerhet. Direktoratet for Byggkvalitet (DiBK), Trondheim
55. Norge S (2012) CEN/TS 1187:2012 Test methods for external fire exposure to roofs. Standard Norge, Oslo
56. The European Parliament and the Council of the European Union, ''Regulation (EU) No 305/2011 of the European Parliament and of the council of 9 march 2011 laying down harmonised conditions for the marketing of construction products and repealing Council Directive 89/106/EEC'', European Union, 2011. Available: https://data.europa.eu/eli/reg/2011/305/oj

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